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DESIGN AND OPTIMIZATION OF THE FREE END OF AN ENGINE-GENERATOR SET

WÄRTSILÄ 20V34DFB FOR A POWER PLANT INSTALLATION

School of Technology
2017

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Opinnäytetyö tehtiin Citecillä toimeksiantona Wärtsilälle. Opinnäytetyön tavoitteena oli suunnitella lyhempi yhteinen alusta 20V34DFB–moottorille sekä muokata putkia alustaan sopivaksi. Suunnittelu tehtiin konseptitasolla. Putkien sekä alustan ominaistaajuudet laskettiin ja analysoitiin. Opinnäytetyö sisältää rakennemallin luomisen NX:llä, elementtimentelmämallin luomisen Abaquksella sekä ominaistaajuuslaskentaraportin vapaanpään putkille ja alustalle.

Yhteisen alustan ja vapaan pään putkien suunnittelussa on tärkeää, etteivät moottorin kriittiset herätetaajuudet osu rakenteellisten ominaistaajuuksien lähelle. Tämä olisi rakenteelle erittäin kuluttavaa. Suunniteltujen putkien ja alustan ominaistaajuudet analysoitiin sekä ongelmalliset ominaismuodot säädettiin paremmiksi.

Ominaistaajuuksien analysoinnin seurauksena löytyi kolme haastavaa komponenttia. Nämä komponentit optimoitiin muokkaamalla tuentaa sekä niiden rakennetta. Paikalliset ominaismuodot saatiin muutosten seurauksena siirrettyä turvallisille taajuus alueille pois moottorin kriittisiltä herätetaajuuksilta. Opinnäytetyön kaikki tavoitteet saatiin saavutettua.

Raportista on poistettu kaikki salainen tieto.

Avainsanat NX, Abaqus, suunnittelu, ominaistaajuudet, resonanssi

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ABSTRACT

Author	Anssi Rintamäki
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The thesis was done at Citec as an assignment for Wärtsilä. The objective of this thesis was to design a shorter base frame for the 20V34DFB engine and adjust the piping accordingly on the conceptual level. The natural frequencies of the pipes and the base frame were calculated. The thesis included building the structure model using NX and Finite Element Method model using Abaqus and also creating a natural frequency calculation report for the free end piping and the base frame.

It is important that the base frame and the free end pipes do not start to resonate with the critical excitations from the engine. That would be very wearing on the structure. In order to avoid this, natural frequencies of the newly designed base frame and pipes were calculated and problematic modes were tuned.

Three challenging components were found after calculating the natural frequencies of the 20V34DFB generating set. They were optimized by modifying the structure and optimizing additional supports. The local natural modes of the components were shifted to safe frequency areas away from the main engine excitations. All the objectives of the thesis work were completed.

All secret information has been removed from this report.

Keywords NX, Abaqus, design, natural frequencies and resonance

TERMS AND ABBREVIATIONS

FO	Fuel Oil
Genset	Engine-generator Set, Generating Set; an Engine Coupled with a Generator
Assembly	Gathering of Parts and Subassemblies
HT	High Temperature
LT	Low Temperature
LO	Lubricating Oil
FEM	Finite Element Method
3D	Three Dimensional
CAD	Computer Aided Design
CAE	Computer Aided Engineering
Node	Coordinate Location of DOF
DOF	Degree of Freedom
Mode	Form of Natural Frequency in Structure
MR	Rolling/Torsion Movement
MB	Pitching/Bending Movement
Free End Pipes	Pipes in the Free End of the Genset
Excitation	Vibration from Engine
Natural Frequency	Frequency of System’s Vibration without External Force

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1 INTRODUCTION

One of the most notorious and well known events in the history of vibrations and resonance is the collapsing of the Tacoma Bridge. This “Galloping Gertie” was opened to the public on July 1, 1940. This example shows how important the evaluation of natural frequencies is.

The construction of the bridge started in 1938 and it was completed with much lower budget than expected. Leon Moseff redesigned the original plans with drastic modifications so it could be made with almost half the price. The revised design was very light and flexible. Following the opening of the Tacoma Bridge, traffic was increased by 145% as it became regular tourist attraction due to peculiar wave-like motion of the bridge on stronger winds. After four months, early on the morning of November 7, the wind was perhaps stronger than any previously encountered by the bridge. Traffic was shut down as the bridge started oscillating torsionally. When the bridge began cracking, vibrations made the edges of the bridge have 8,5m height difference at the maximum magnitude. At 11 a.m. the entire bridge came crushing down. /8/

With modern technology and software, similar catastrophes could be avoided. Natural frequencies of complex structures can be solved with relative ease and resonances between excitations and responses can be prevented. This thesis addresses the interactions between excitations from the engine and responses of the free end pipes and base frame and prevention of accumulating vibrations.

1.1 Project Background

Over time, the base frame for the 20V34DF generating set (genset) has been made longer in the free end due to modifications and new components. A longer base frame means that the structure is less stiff and exposed more easily to vibrations. By shortening the base frame, it becomes stiffer and vibration behavior can be made better. The pipe design needs to be adjusted to fit the shortened base frame. Supporting the largest pipes from critical points should be considered as they have high mass and are liable to vibrations.

Resonance might damage the structure of the base frame even if it is shorter. This is why the natural frequencies of the base frame and pipes need to be calculated and resonances avoided as well as possible by modifying the structure. Excitations from the engine are known and can be compared to the calculated natural frequencies.

1.2 Approach and Execution

The design work and construction of the structure model were concluded using the Siemens NX 3D CAM software. NX is the primary software for mechanical design work at Citec for Wärtsilä related projects. The finished 3D models were imported from NX in to the Abaqus where they were meshed and tied together. Abaqus as a calculation tool is widely used in Wärtsilä and it produces reliable results in calculating natural frequencies of complex structures. The FEM model was calculated and results were analyzed. The design and supporting was optimized according to the relation between natural frequencies and excitations from the engine.

1.3 Objectives

The objectives of this thesis are:

1. To redesign a 432mm shorter base frame for 20V34DFB 1–C on the conceptual level
2. To redesign free end pipes including: Pipes assembly for free end, Leak fuel pipes, Starting air pipe, Control air pipe, Pilot fuel line, Drain pipe and Fuel pipes and their covers on conceptual level, this included designing the piping support structures
3. Construct a structure model with NX for Teamcenter
4. Consider the effects of the genset changes to auxiliary equipment
5. Construct a Finite Element Method model with Abaqus
6. Calculate the natural frequencies of the genset free end to optimize the design accordingly
7. Create a report for detailed design and further development

1.4 Base frame and Free End Pipes Compatibility

The purpose of the thesis was to create a unifying base frame and pipe design for many different engines. The pipe routings should fit to all V engine configurations currently in the W32/34 portfolio, as well as, in addition to the 34DF, the 34SG gas version and W32 diesel version. The redesigned base frame and free end pipes will be compatible with diesel, spark gas and duel fuel engines.

1.5 20V34DFB 1–C Engine and Generating Set

20V34DFB 1–C Engine is a dual fuel (DF) engine that has 20 cylinders in V–configuration (20V). The diameter of one cylinder is 34 cm. The engine in this case has 1–circuit cooling system (1–C) and is in design stage B at the moment.

The Wärtsilä dual fuel engines are four stroke power converters that can be run for example on natural gas, diesel oil or heavy fuel oil. One of the main features of the proven and reliable dual fuel technology is that the engine can be switched from fuel oil to gas operation and vice versa smoothly during the engine operation. /13/

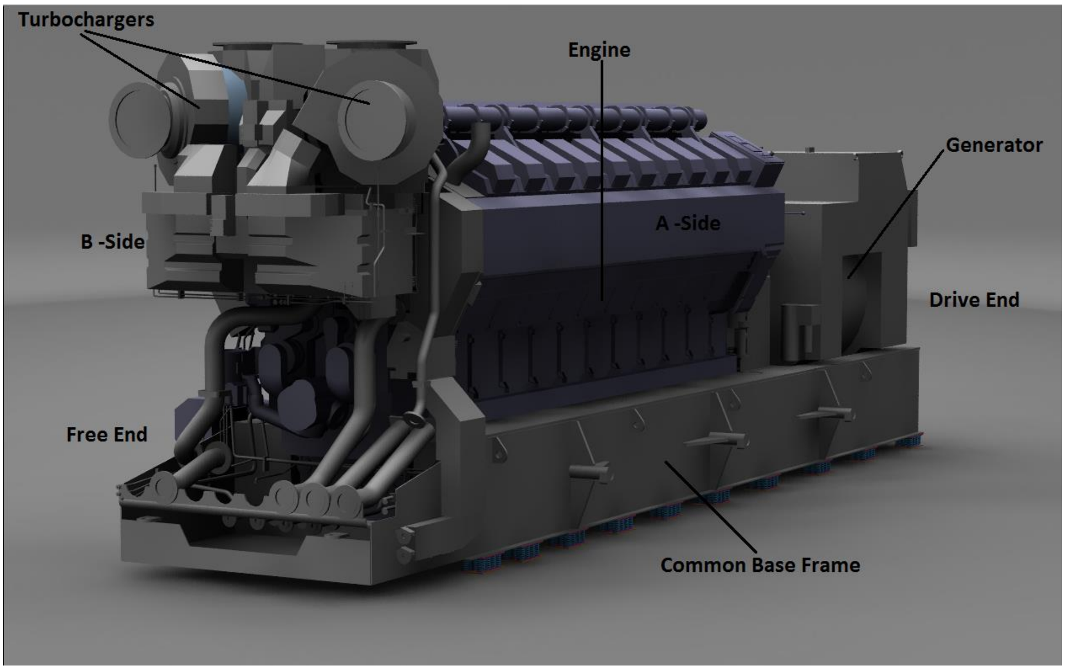

Figure 1. Main components of a generating set.

Diesel and Spark Gas versions of the engine are also part of Wärtsilä's engine portfolio. Other possible cooling systems for Wärtsilä engines are 2–circuit (2–C) and open interface cooling system which is used in central heat processing facilities.

2 PROJECT STAGES AND SCHEDULE

2.1 Schedule

The original schedule was to use four weeks for the design work, one week for constructing the FEM model and seven weeks to calculate and optimize the model, and analyze the results. The original schedule was decided in the kickoff meeting with both partners.

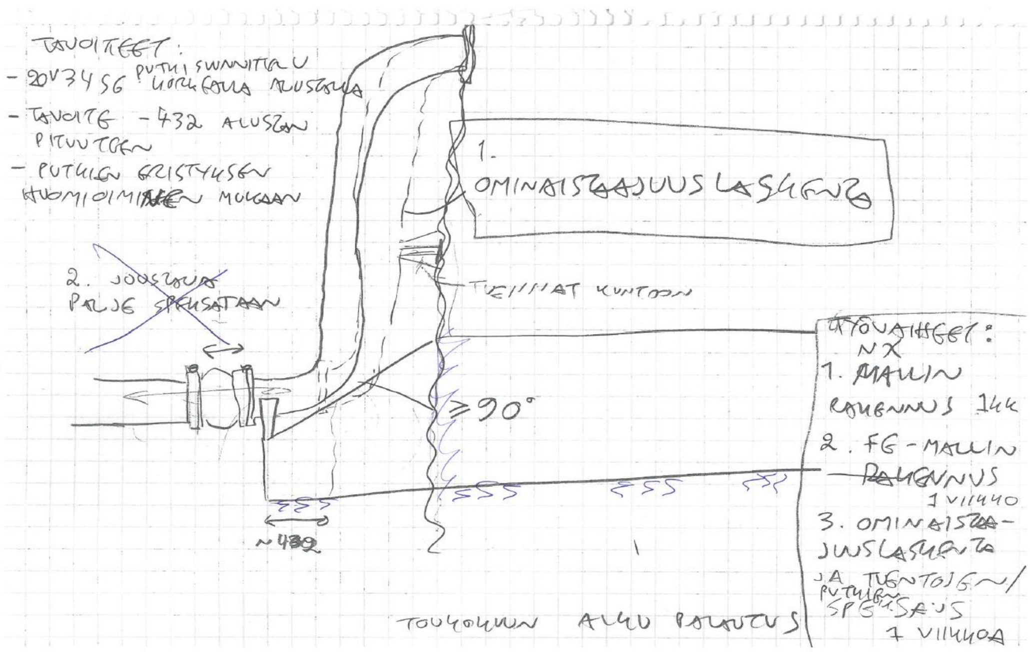

Figure 2. Kickoff meeting plan.

When the work started, the project stages were defined in more detail and some rescheduling was conducted. The Rolling Wave strategy was used for planning. As the project went on, the work tasks and schedule became more specified.

Week	5	6	7	8	9	10	11
Starting date	1.2.2017	6.2.2017	13.2.2017	20.2.2017	27.2.2017	6.3.2017	13.3.2017
Task	-Induction -access rights -Background	-Induction -Designing -Structural model -Background	-Designing -Structural model	-Designing -Structural model	-Designing -Structural model -Supports	-Finishing up design work	-Moving to Wärtsilä -Constructing FEM Model

Week	12	13	14	15	16	17
Starting date	20.3.2017	27.3.2017	3.4.2017	10.4.2017	17.4.2017	24.4.2017
Task	-Constructing FEM Model	-FEM Model -Superelement construction	-FEM Model -Superelement construction	-Natural Frequency Calculation -Supports	-Natural Frequency analysis -Supports -Optimization	-Natural Frequency analysis -Optimization -Presentation

Figure 3. Second stage of project plan.

2.2 Project Stages

The project was divided into three stages that were Structural Design, Construction of the FEM model and Calculation, Analysis.

2.2.1 Structural Design

The first stage of the project was design work. The estimated duration for the structural design was reasonable and the first stage was ready in 5 weeks' time. The starting of the work and familiarization with the new working environment took some time in the beginning.

2.2.2 Construction of the FEM model

The second stage of the project was the construction of the FEM model in Abaqus. The estimated duration for the model construction was changed to one month at a very early stage of the project. The reason was a mistake in the estimation of the work load between the construction and the calculation in the kickoff meeting. The overall work time stayed the same, just the ratio for time of the project stages changed.

2.2.3 Calculation, Analysis and Optimization

The third and the final stage of the project was the calculation of the natural frequencies, analysis and optimization. The estimated duration for this stage was one month. After the calculation, analysis and optimization, the results were documented.

3 PARTNERS

The project was done at Citec as an assignment for Wärtsilä.

3.1 Citec

Citec provides multi–discipline engineering and information management services to the Energy and Oil & Gas industries, as well as other technology–dependent industries. The company has delivered projects to 116 countries all over the world. Citec has six business sectors which are energy, oil & gas, civil, manufacturing, vehicles and process industry. /1, 2/

The number of Citec employees amounts to approximately 1300 and the turnover for 2016 to about 72 million EUR. Citec is headquartered in Vaasa, Finland, and has offices in Finland, Sweden, Norway, the UK, France, Germany, Russia, India, Singapore, Kazakhstan and Saudi Arabia./2/

Figure 4. Citec office locations /3/.

The company Tri–Tech was founded in 1984 by Rune Westergård and Rolf Berg within the field of mechanical engineering and grown larger ever since. In 1994 the name of the company was changed to Citec. A fund managed by Sentica Partners entered as a new majority shareholder with a 67 percent share and Martin Strand was appointed CEO as of June 1, 2011. /4/

3.2 Wärtsilä

Wärtsilä was established in 1834 and is today a global leader in advanced technologies and complete lifecycle solutions for the marine and energy markets. By emphasizing sustainable innovation and total efficiency, Wärtsilä maximizes the environmental and economic performance of the vessels and power plants of its customers. In 2016, Wärtsilä's net sales totaled EUR 4.8 billion with approximately 18,000 employees. The company has operations in over 200 locations in more than 70 countries around the world. Wärtsilä is listed on Nasdaq Helsinki. /5/

3.2.1 Energy solutions

Energy Solutions in one of Wärtsilä's three businesses along with Marine Solutions and Services. Energy Solutions specializes in designing and building power plants for utilities and industry. Smart Power Generation power plants from Energy Solutions are based on multiple internal combustion engines and are able to run on any gaseous or liquid fuels, including biofuels. They provide industry–leading energy efficiency, fuel and operational flexibility, helping to integrate wind and solar power into the grid. Energy Solutions has delivered over 4700 plants ranging from 10 to 600 MW in 170 countries worldwide.

The design and optimization work in this thesis was done for the genset that is customized for Energy Solutions' needs.

4 THEORY

4.1 Vibration

Every mechanical system has a natural frequency or a set of natural frequencies. If the system is agitated, by for example dropping or hitting, and displaced from its stable state, it will start vibrating on account of trying to return to its stabilized state. These vibration frequencies are known as the natural frequencies. They are unique to each different system. In reality, these vibrations are always damped and the system will return to its stabilized state if no outside forces are involved.

A vibrating system affects all connected systems. This outgoing vibration is known as excitation. The value and strength of the excitation depends on the generating source. These sources can be for example engines, pumps or automated valves.

When the system is mechanically connected to the source of excitation, it will start vibrating. This occurrence is known as response in the system. When the natural frequencies of the system and excitation frequencies are matched, the system is in resonance.

4.2 Finite Element Method in Natural Frequency Calculation

The Finite Element Method is a numerical method for solving engineering problems. It is useful for overcoming challenges of complex structures when there is no direct way of solving them.

In the finite element method, a single complex structure is replaced with approximately equivalent network of simple elements. The overall pattern of elements is referred to as the Finite Element Mesh. Depending on the object and what needs to be calculated, one–, two– or three dimensional elements can be used. The elements can be for example rods, triangles or tetrahedrals. The outcome of an element mesh can also be a combination of different elements.

The accuracy of the calculation depends on the number and the size of the elements included in the mesh. The more elements in the model, the smaller each one will be and the more accurate the results. More elements means more calculations to be done. The final element meshes are usually compromises; enough elements to give an adequate accuracy and also have a reasonable computing time.

Each element is defined by different number of points known as the nodes. Every node can move laterally and vertically and in three dimensional elements also axially. The exception is immovably fixed nodes around the outside edges where the object is connected to the surroundings. These are called the boundary conditions and they are needed to complete the description of physical problem. Elastic materials and loads for the elements need to be specified.

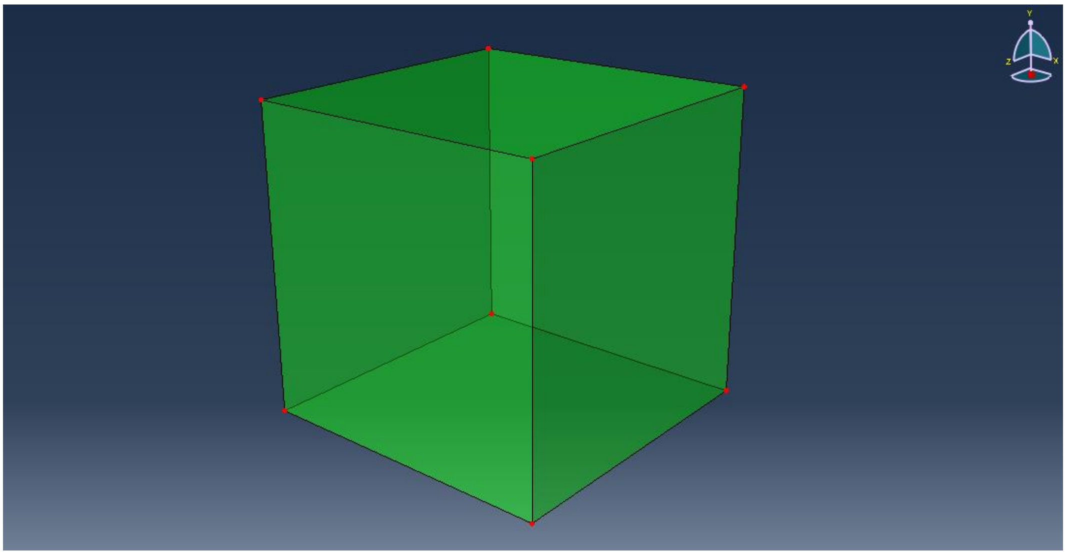

Figure 5. Nodes at the corners of solid element.

The aim of the finite element method is to describe the behavior of whole system. This can be achieved by calculating the coordinates of the elements nodes. The equations of the node's coordinates form a matrix. The coordinates of the nodes are combined and added into vectors that describe the displacement of the whole element. This process is carried out for every element in the mesh. Individual matrixes of each element are combined into a large matrix that represents the whole system.

Any two neighboring elements have nodes in common. The values of those nodes appear in both element matrices. Two matrices can then be combined by merging a technique known as reduction. The merged matrix will be combined with the next matrix and so on until the solution for the last single node is solved. This result can be used as a key and equations can be worked backwards until the displacement of every node is obtained and corresponding stresses can be calculated for the whole system.

The calculations involve so large matrices that a powerful computer is required. Advantages for the finite element method are ability to work with arbitrary shapes and ease of investigating different materials and loads. /9 – 11/

5 THE STRUCTURE MODEL OVERVIEW

The structure model of the 20V34DF genset can be divided into three sub models in this thesis. These sub models are the Free End Pipes, Common Base Frame and Background.

In all the models and figures, the X–vector represents crankshaft line axial direction, Y–vector the lateral direction and the Z–vector the vertical direction.

5.1 Common Base frame

The common base frame is the steel structure on which the engine and generator commonly lie. The free end pipes are attached to the free end (see terminology) of the engine and the common base frame. The base frame lies on flexible (spring) elements, which in turn lie on the concrete engine foundation.

The common base frame used in this thesis is a new design. It was designed and verified to work structurally with the newest E Design Stage of the Wärtsilä 32. It is planned to be used also with the W34 engines, but this is not yet fully verified via FEM. It will be shortened according to the plans described above.

5.2 Free End Pipes

All pipes in the free end were redesigned to fit the shorter base frame. These “free end pipes” consists of Pipe Assembly for the Free End; Leak fuel Pipes, Dirty & Clean; Control Air Pipe; Pilot Fuel Line; Drain Pipe and Fuel Pipes and Covers.

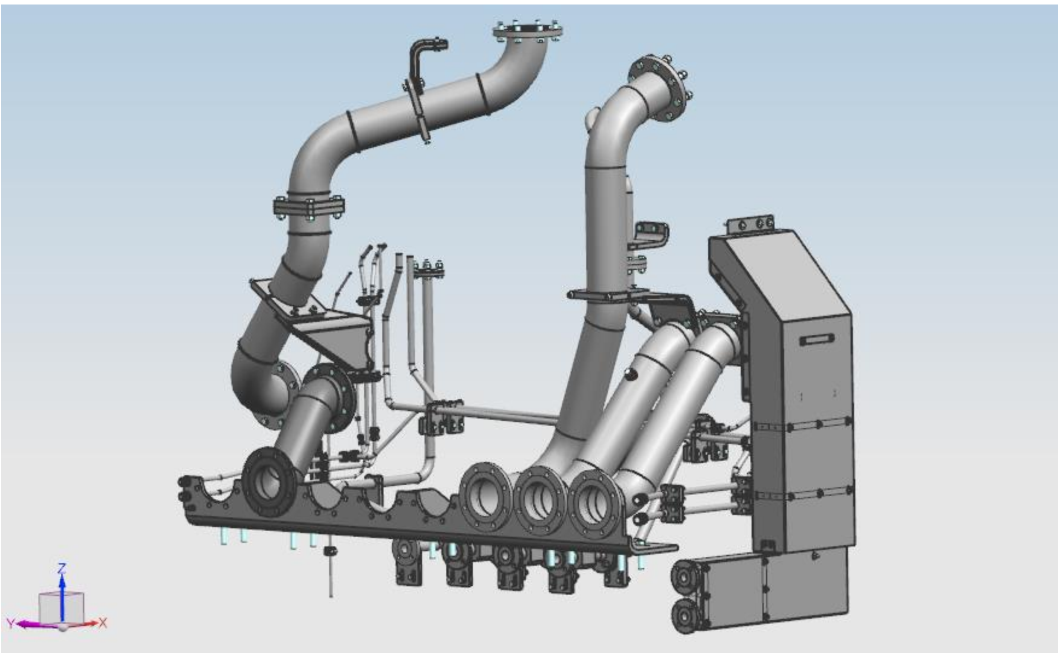

Figure 6. Overview of the Free End Pipes structure model.

5.3 Background

5.3.1 Description

New pipe routes and a shorter base frame were designed around the background assembly so it was necessary to construct. The background helps to understand the entirety of the free end and without it, the newly designed pipes might in reality clash with some background components. The background assembly in NX consists of all essential components in the free end of the genset, for example oil & water pumps, valves, covers and pipe connections.

5.3.2 The Background Assembly

There was no suitable existing model of the 20V34DFB genset which could have been used as a design background. It therefore had to be built. Most of the components could be copied from several existing design assemblies. The background was built to match the standard genset, with each component listed in the engine product structure. If the components were not in the existing design assemblies, they could be looked up from the product specifications of the 20V34DFB 1–C genset. After the right component had been found, it was added to the background assembly and positioned.

Once the background assembly was ready, all the components from the product structure were checked one by one to ensure that nothing necessary was missing. After the validity of background was confirmed, the design work for the base frame and pipes could begin.

6 BASE FRAME DESIGN

6.1 Structure

The base frame was shortened by 432mm on the x axis. The 432 mm figure was selected to match the piping connection points with the newer Wärtsilä 31 Genset. The structure at the free end was simplified and excessive components were removed. The base frame was designed according to the Wärtsilä quality instructions. The model includes welding assembly and machined assembly. The 3D models of both old and new base frame are presented in **Figure 7**.

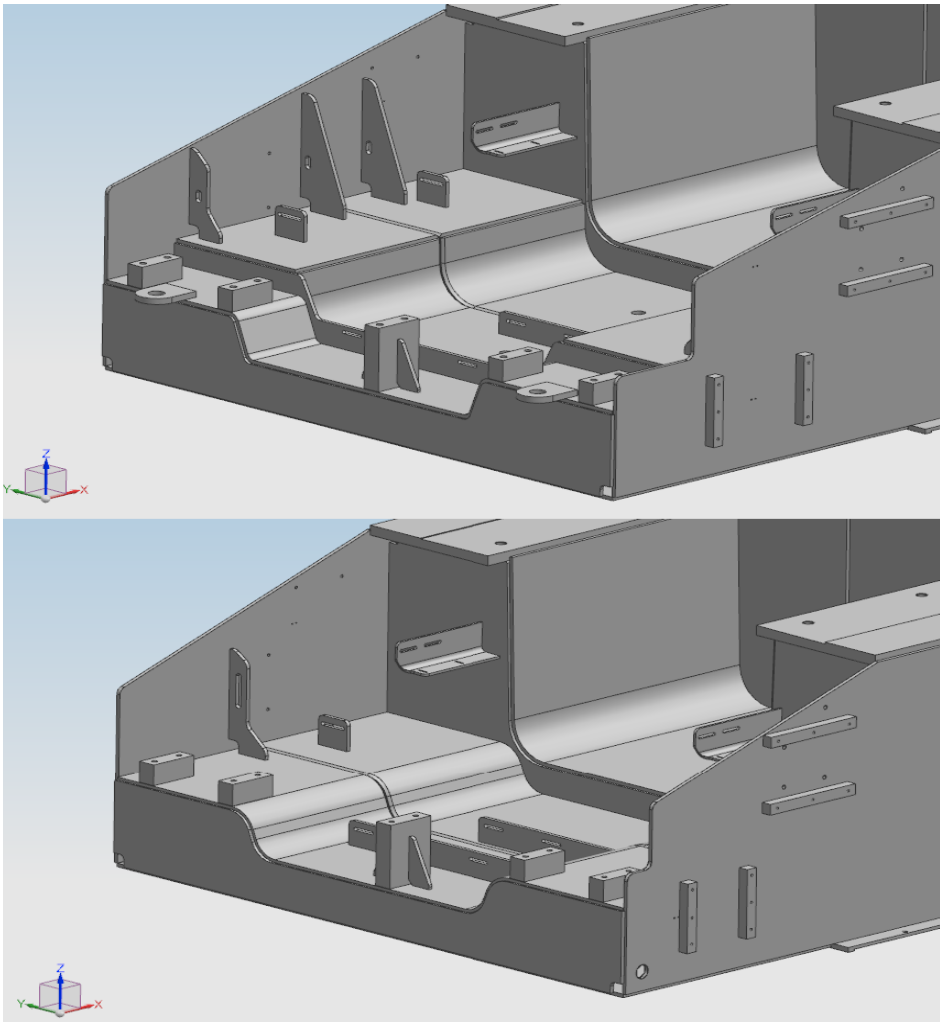

Figure 7. Machined base frame. (Upper: old & lower: new.)

6.2 Side Plates

The angle of the chamfer on the side plate was adjusted to make the plate less flexible. A hole was made onto the side plate to replace a separate plate for fastening during transportation. The size of the opening for Leak fuel Pipes, Dirty & Clean was reduced as it was unnecessary large.

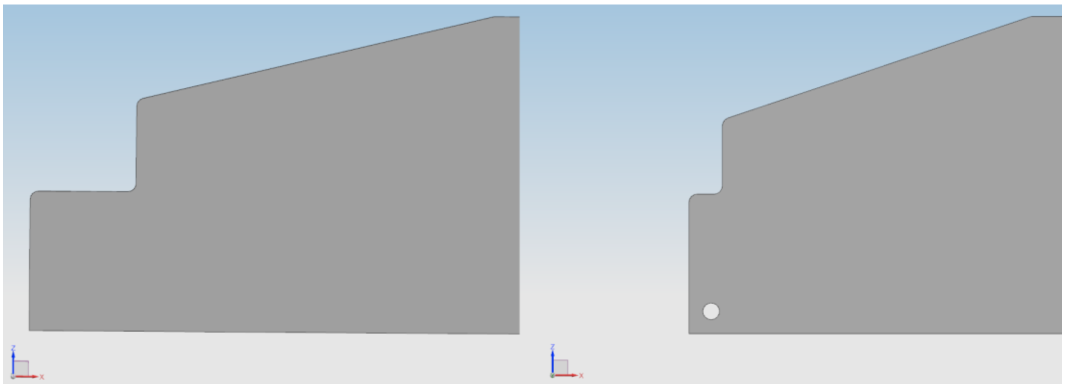

Figure 8. Both side plates of the Common Base Frame. (Old & new.)

6.3 Chute

The number of plates in the end chute was reduced from three to two. The new plates consist only of one sheet and they are possible to make by bending with the bend radius of 100mm. The upper level of the chute is positioned now at the same level consistently.

6.4 Brackets

The number of support brackets for different pipe clamps was reduced. The design was modified to fit the new base frame. Two of the support blocks for the Mounting Plate between the middle one and the outermost two were moved 55mm to the sides out of the bends of the chutes. The L–brackets for Pilot Fuel Line and Leak fuel Pipes, Dirty & Clean remained unmodified as requested.

6.5 Supports

As the base frame was shortened and the number of the chute plates reduced, the need for lateral supports decreased. One support between the chute plates was removed. Four side plate/pipe clamp supports were removed as they were no longer needed.

7 PIPE DESIGN

The pipes were designed so they can be made by bending as often as possible as it is the least expensive option. When bending was not possible, pre–manufactured pipes could be used but they require onsite welding and are the most expensive option. Making the pipe by casting was also a possible option.

The length of most pipes was shortened by 432mm on the x axis. If some pipes had different length reductions, they are mentioned later on. The manufacturing of the newly designed pipes was made easier whenever it was possible by adjusting bends and routings.

The pipe design rules were followed according to the Wärtsilä Internal Pipe Design Guide when possible. The rules included for example information about bend radiuses with certain pipe diameters and required minimum length between the supporting points for different size pipes /6/.

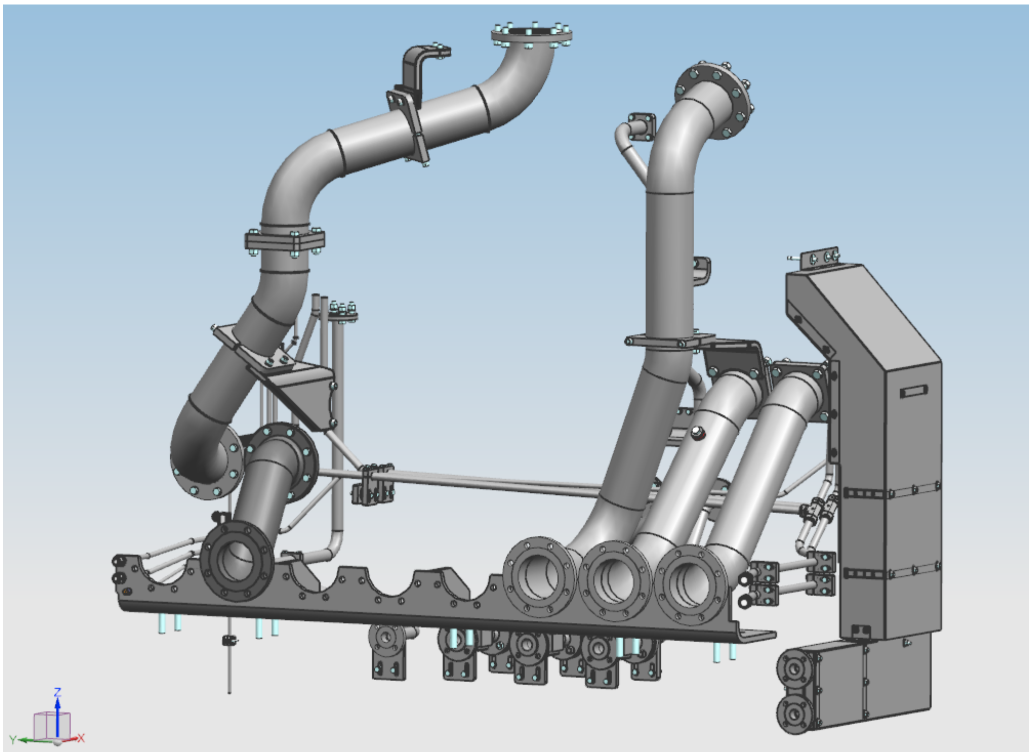

Figure 9. Assembly of all pipes in the free end.

The design guide utilizes the following international standards:

- EN 13480: Metallic industrial piping
- EN 1798–1: Welding. Basic welded joint details in steel– Part 1: Pressurized components.
- EN ISO 9692–1: Welding and allied processes. Type of joint preparation. Part 1: Manual metal arc welding, gas–shielded metal arc welding, gas welding, TIG welding and beam welding of steels.
- EN ISO 2553: Welding and allied processes. Symbolic representation on drawings. Welded joints.

There was no need to consider basic material for the pipes. Wärtsilä has internal standards that specify the material for each piping system and their components.

7.1 Pipe Assembly for the Free End

The Pipe Assembly for the free end was the largest assembly of pipes in the free end and it is presented in **Figure 10**.

7.1.1 High Temperature Water Outlet

The HT water outlet was made shorter on the x axis. The routing of the pipe stayed relatively similar to the longer design. The 3D models of both the old and new pipe designs of HT water inlet are presented in **Figure 11**.

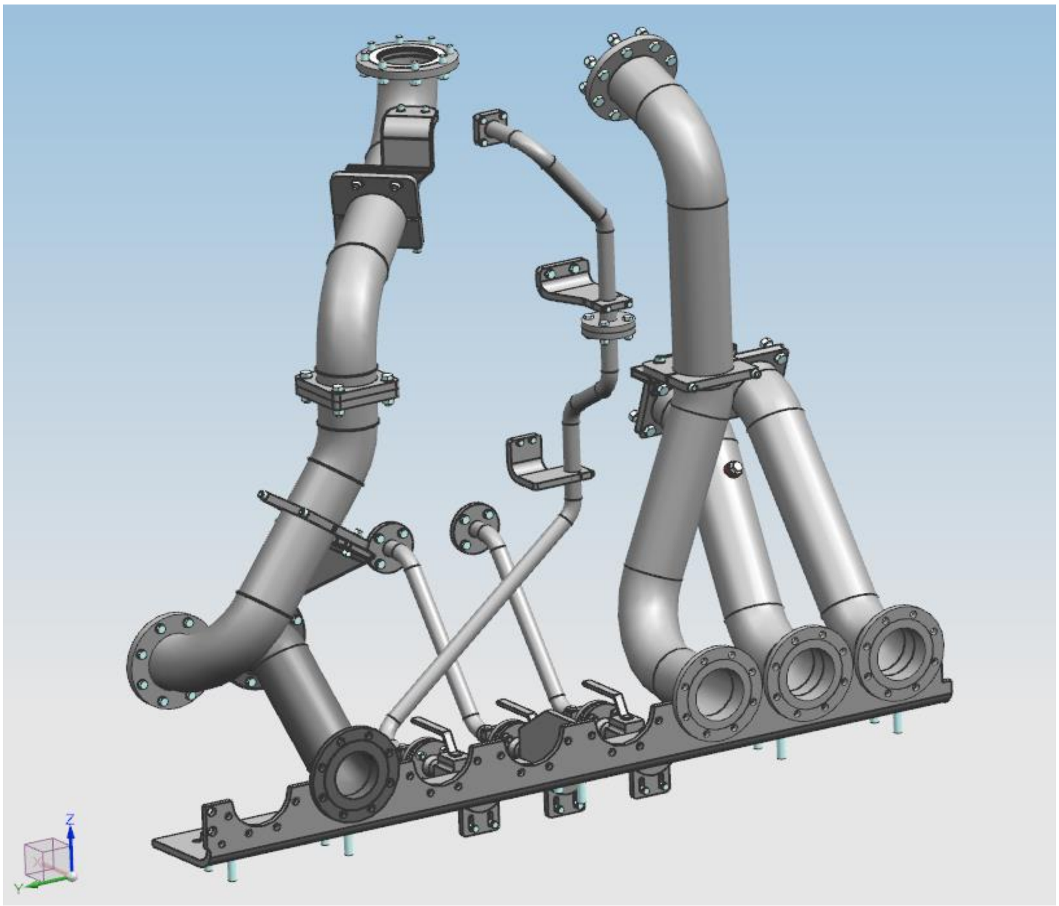

Figure 10. Pipe Assembly for the Free End

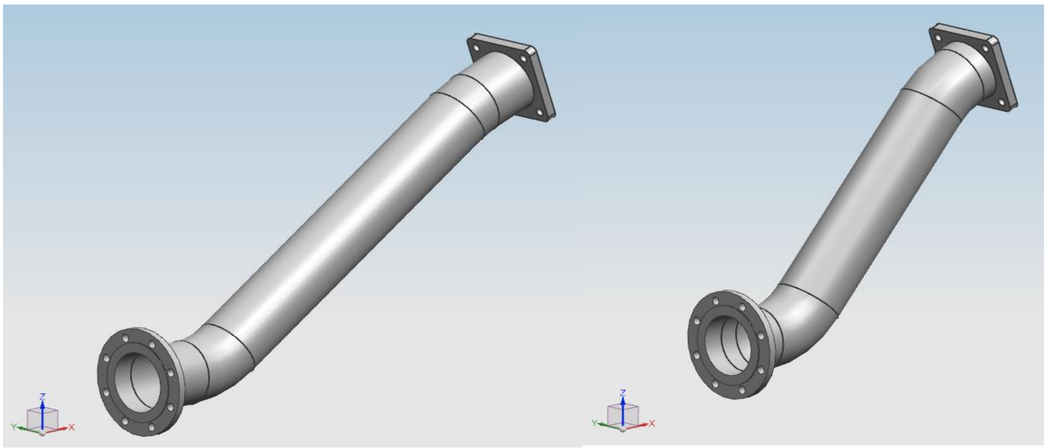

Figure 11. High Temperature Inlet. (Old & new.)

7.1.2 High Temperature Water Inlet

The HT water inlet was made shorter on the x axis. The pipe includes welding boss but the location will be decided when the manufacturing drawings are made. The

3D models of both old and new pipe designs of HT water inlet are presented in **Figure 12**.

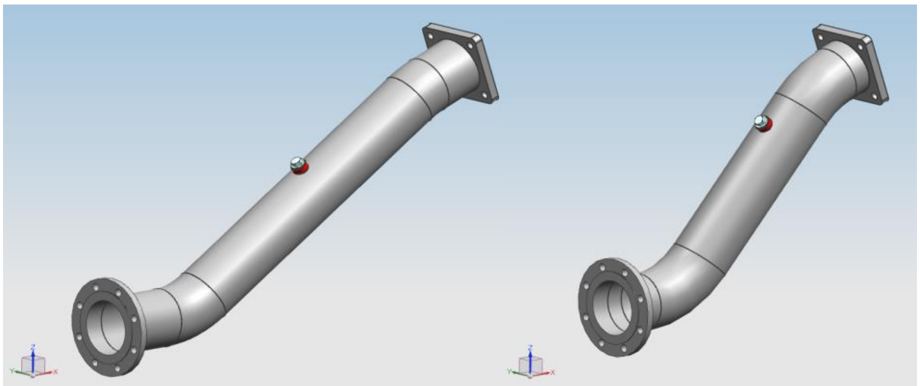

Figure 12. High Temperature Water Inlet. (Old & new.)

7.1.3 Low Temperature Water Inlet

The LT water inlet was a very problematic pipe due to its short length, see **Figure 13**. The new shorter design was not possible by using the bent pipe and normal pipe design rules. There were three different possibilities:

1. Design the pipe using pre–manufactured parts that could be welded together with a very short ring between them
2. Modify the casted LT pipes 150–200mm shorter so there would be more room for the LT Water Inlet, see **Figure 13**
3. Manufacture LT Water Inlet by casting

Modifying the casted LT pipes was out of the question because as a part of a product design W32/34 it would affect many existing sections. Only two options were left, casting or welding the pipe. The estimated manufacturing costs for both remaining alternatives were acquired from Wärtsilä. It seemed that the cost of the welded bends would rise very high. On the other hand, the cast bends would weigh approximately twice as much as the welded ones due to the wall thickness.

With estimated potential of upcoming manufacturing quantities, the alternative to cast the LT water inlet would be more cost–efficient so this option was selected. It was discussed that the pipe would be designed at a very conceptual level before the knowledge and expertise with casting would be acquired. The 3D models of the old pipe and the both new alternative designs with cast LT pipes are presented in **Figure 13**. The new pipe alternatives are presented more closely in **Figure 14**.

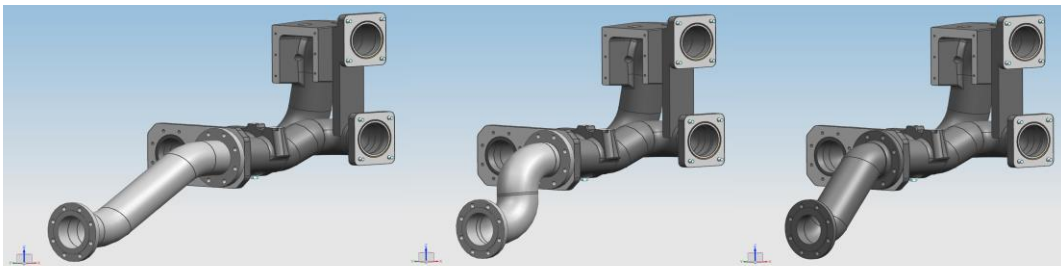

Figure 13. LT Water Inlet and casted cooling water pipes. (Old, Weld & Cast.)

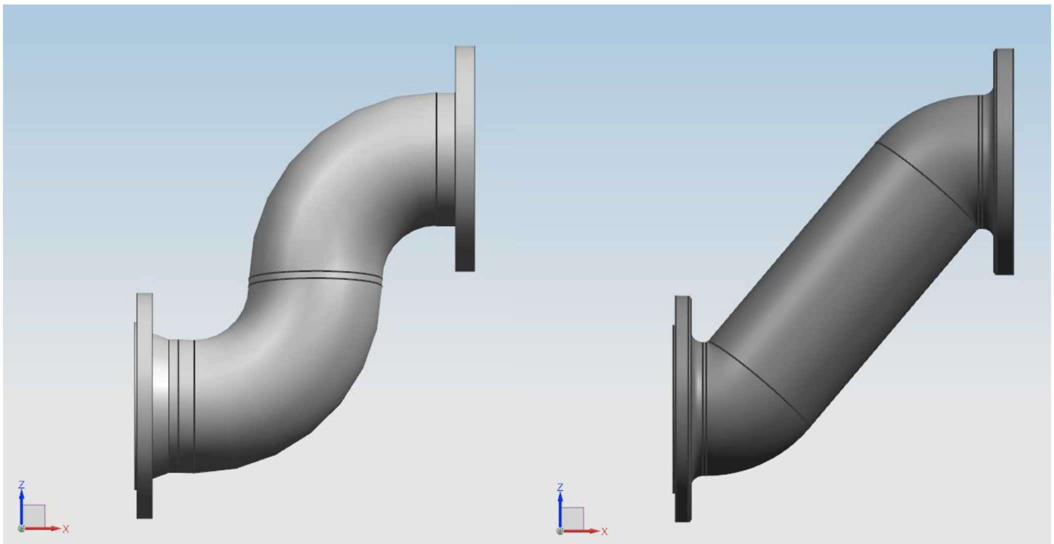

Figure 14. Both alternatives for LT Water Inlet. (Weld & cast.)

7.1.4 Lubricating Oil Pipes 213 & 214

The lubricating oil pipes, 213 from separator and filling and 214 to separator and drain, were made shorter on the x axis. The routing of the pipes stayed relatively similar to the longer design. The 3D models of both the old and new pipe designs of the lubricating oil pipes are presented in **Figure 15**.

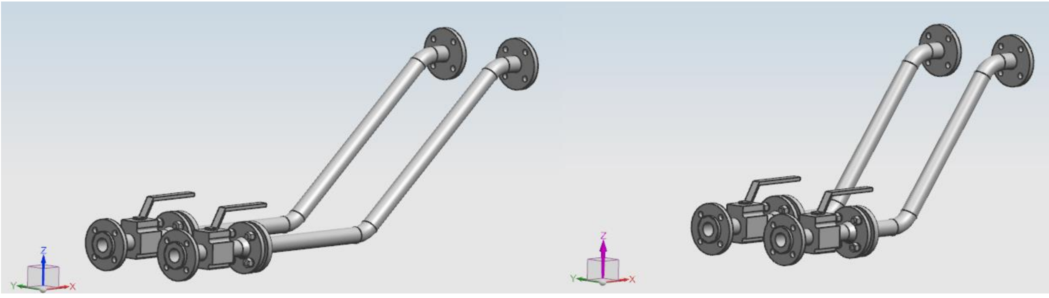

Figure 15. Lubricating Oil Pipes 7. (Old & new, 213 & 214.)

7.1.5 Low Temperature Water Pipe

The LT water pipe was made in two parts, connected by flanges between them. The angles of the bends in the upper part were changed so that the pipe could be made entirely by bending to reduce the manufacturing costs. The pipe clamp bracket was modified to fit with the rerouted pipe.

The lower part of the LT water pipe was supported from the lube oil pipes as can be seen from **Error! Reference source not found.**. The radius of the lower bend as changed so that the welding bend could be removed and the pipe could be made entirely by bending. The 3D models of both the old and new pipe designs of LT water pipe are presented in **Figure 16**.

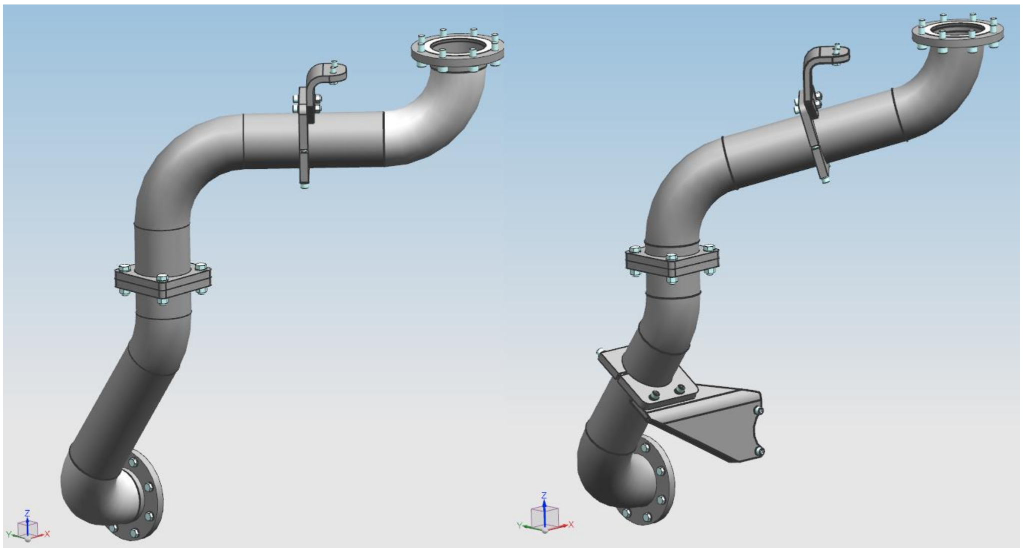

Figure 16. Low Temperature Water Pipe. (Old & new.)

7.1.6 High Temperature Water Outlet from Air Cooler

The upper part of the HT water outlet from the air cooler was rerouted closer to the engine. The angle and direction of the lower bend was modified to make the pipe shorter on the x axis. The routing of the close–by Lubricating Oil Pipes had to be taken into consideration while rerouting the HT water pipe /Appendix 1/. A new support is connected to the flange of the High Temperature Water Inlet. The 3D models of both the old and new pipe designs of the HT water pipe are presented in **Figure 17**.

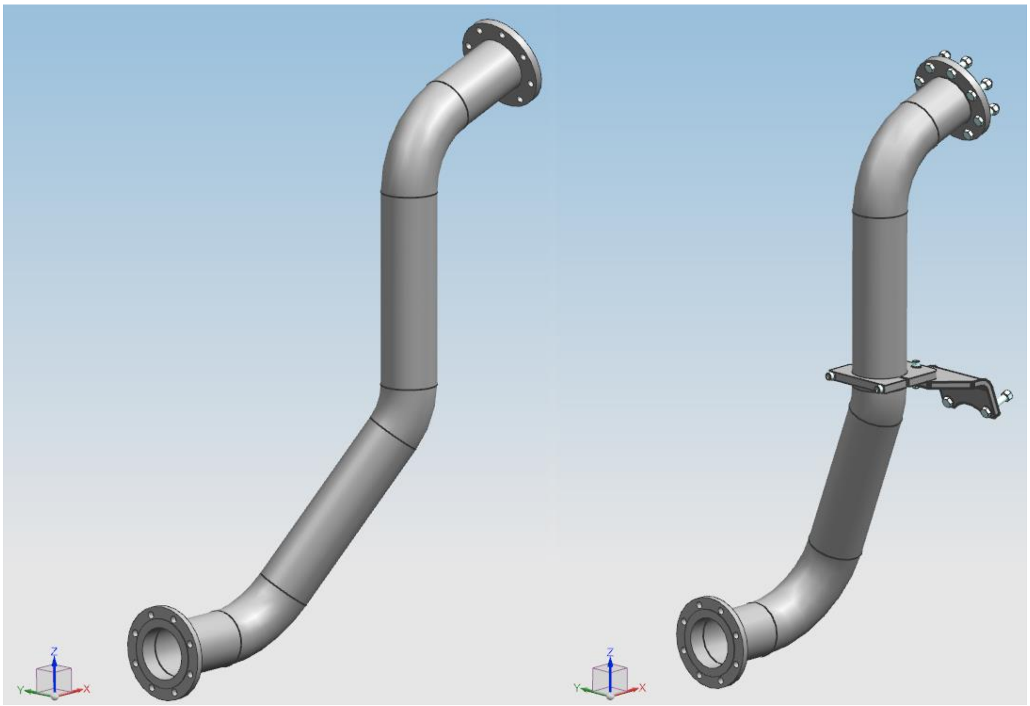

Figure 17. High Temperature Water Outlet from Air Cooler. (Old & new.)

7.1.7 Water Pipe from Preheater

The rerouting of the water pipe from the preheater was challenging because the Lubricating Oil Pipes had to be taken into consideration /Appendix 1/. The length of the pipe was shortened on the x axis. The pipe is manufactured in two parts and the flange connection, approximately halfway through the pipe, was moved higher so that overlapping with the LO outlet could be avoided by routing the pipe behind it. The routing of the pipe was simplified and the angles of the bends were changed in order to make the manufacturing of the pipe easier and cheaper. Both supports and the lower support point was changed. Both support clamps were attached to the pump cover. Due to the different fastening points in the pump cover of the 20V34DF engine, the lower support point was not available and has to be moved. The 3D models of both the old and new pipe designs of the water pipe from the preheater are presented in **Figure 18**.

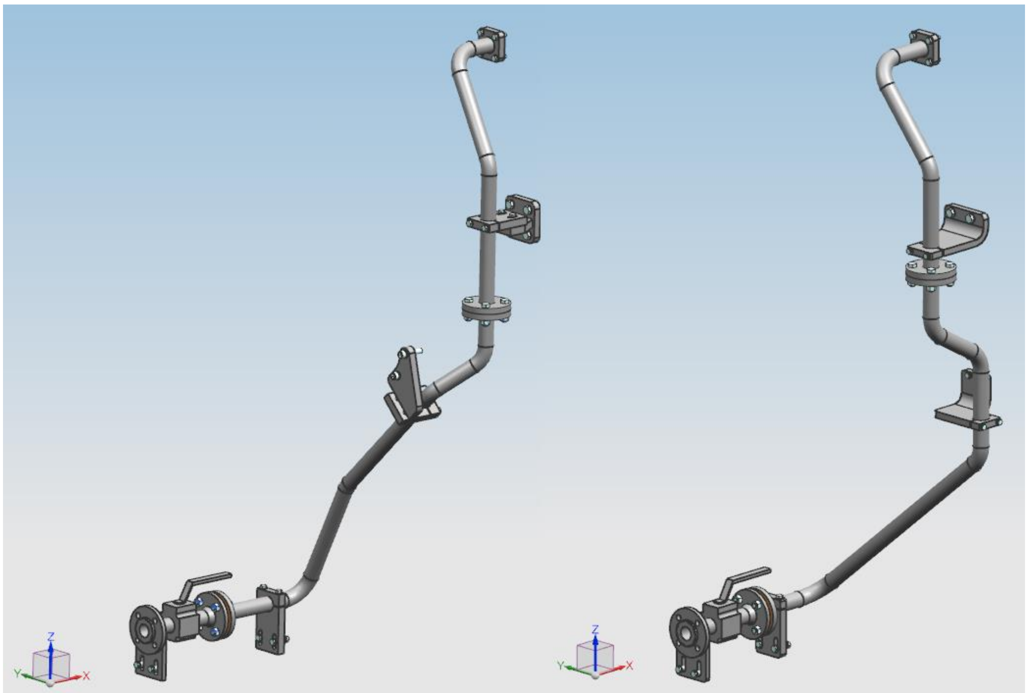

Figure 18. Water Pipe from Preheater.(Old & new.)

7.1.8 Mounting Plate

Two of the pairs of holes in the mounting plate between the middle pair and the outermost two pairs were moved 55mm to the sides. The reason was that the bends of the free end chutes were changed and the mounting plate support blocks had to be moved, see **Figure 20**. The 3D models of both the old and new mounting plate are presented in **Figure 19**.

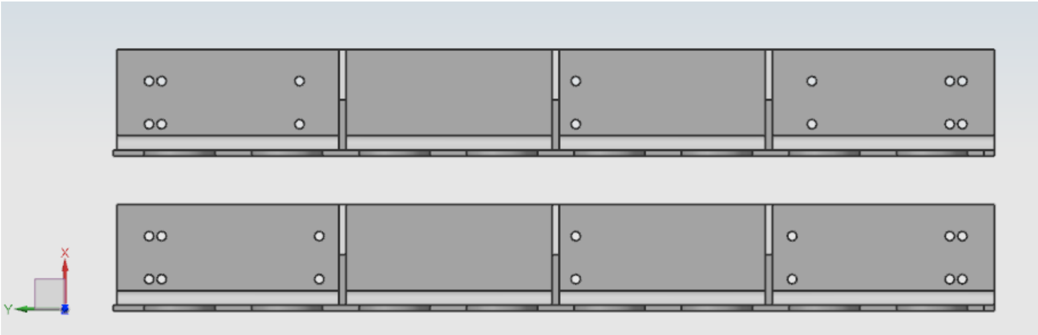

Figure 19. Mounting Plate viewed from top. (Upper: new & lower: old.)

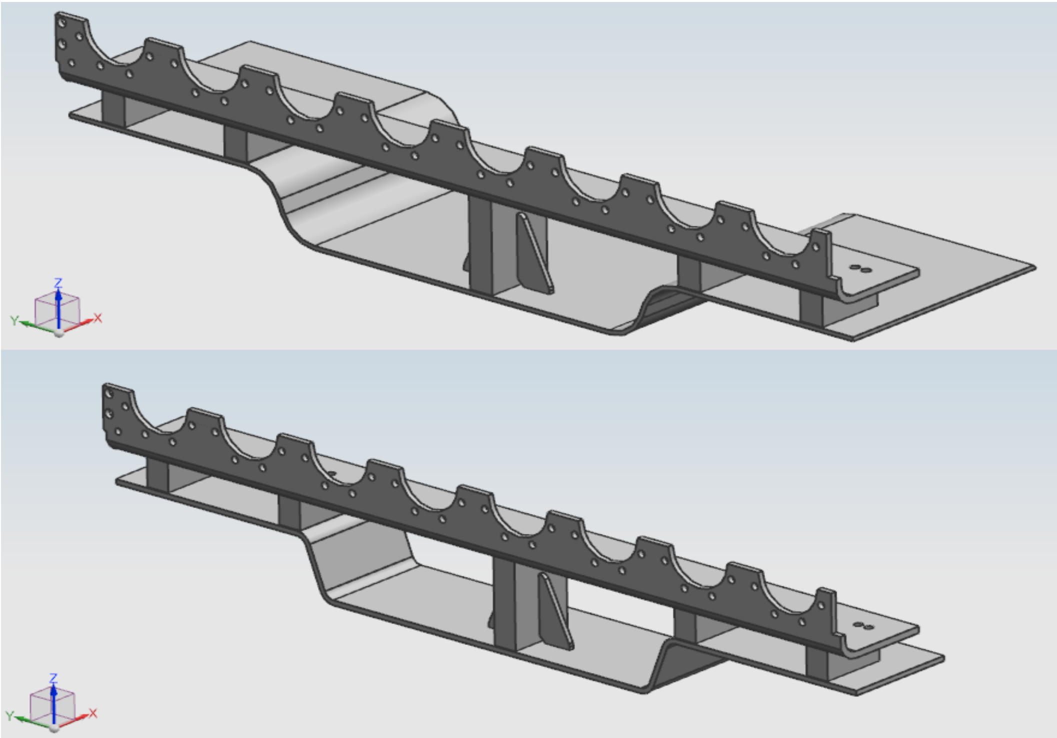

Figure 20. Mounting Plate with support blocks and free end Chute. (Upper: new & lower: old.)

7.2 Leak fuel Pipes, Dirty & Clean

The place of the pipe connections were changed to approximately 205mm closer to the origin on the x axis. The pipes were not shortened 432mm because the idea was to get the pipe connections as close to the engine auxiliary module as possible so that the unsupported connection pipe would be shorter. The pipe connections were also positioned 20 mm higher on the z axis because of the inclination. The routing of the pipes was simplified to make the manufacturing of the pipe easier and cheaper. The placement of the lower clamp supports was adjusted to give the best possible support to the pipes. The 3D models of both the old and new pipe designs of dirty and clean leak fuel pipes are presented in **Figure 21** and **Figure 22**.

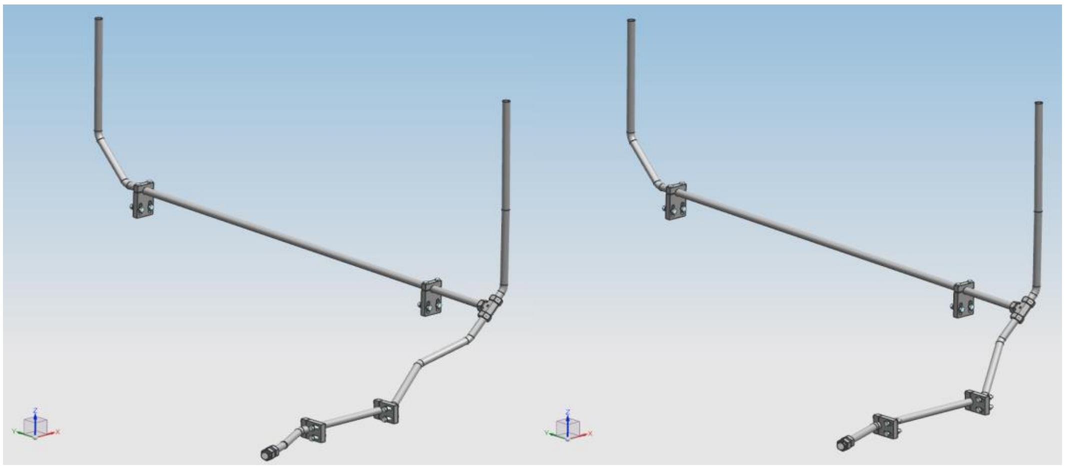

Figure 21. Dirty Leak fuel Pipe. (Old & new.)

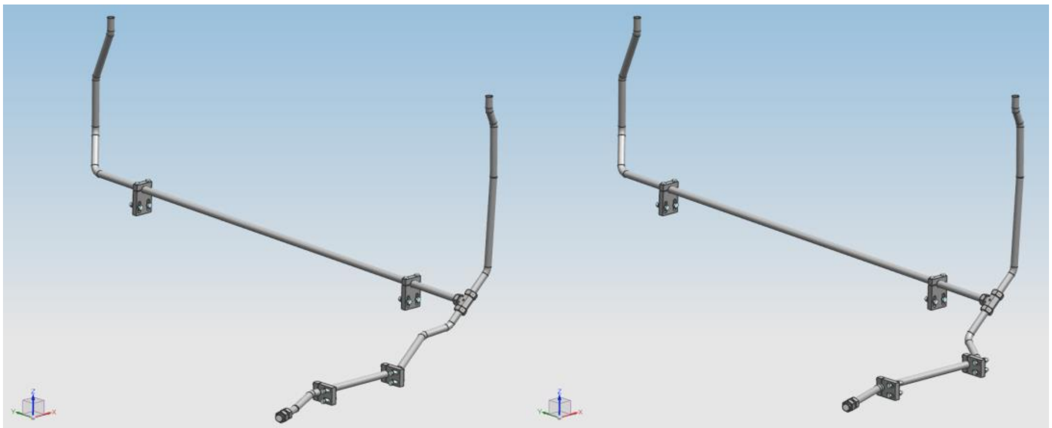

Figure 22. Clean Leak Fuel Pipe. (Old & new.)

7.3 Control Air Pipe

The Control Air Pipe was shortened. The number of support rails was reduced from four to two because the supportable length of the pipe was reduced. The support rails are shared with the Pilot Fuel Line. The 3D models of both the old and new pipe designs are presented in **Figure 23**.

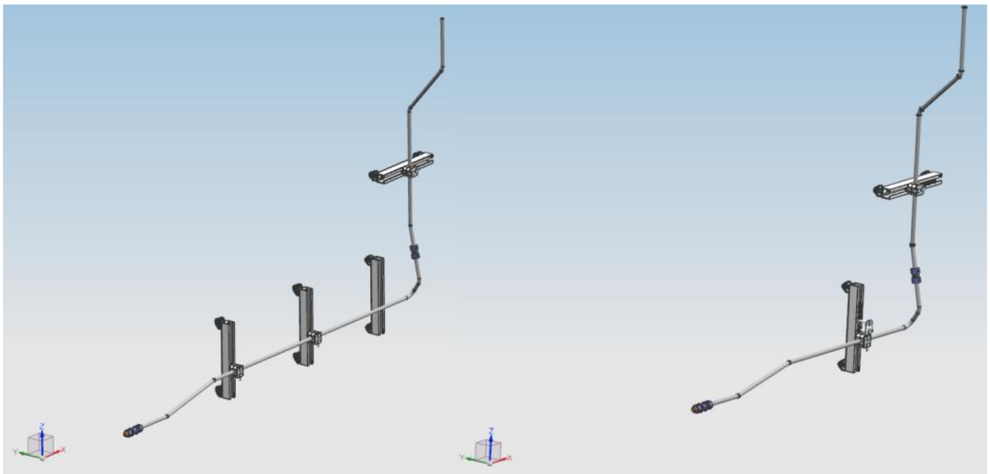

Figure 23. Control Air Pipe. (Old & new.)

7.4 Pilot Fuel Line

The support clamps and route of the piping on the x axis end of the pilot fuel line were overlapping the dirty leak fuel pipe, see **Figure 24**. The rerouting of the pilot fuel pipe was challenging because if routed behind the leak pipes, it would overlap with the drain pipe from the pump cover. The support clamp had to be repositioned and the piping had to be rerouted so that it would go between the leak fuel pipes to avoid any clashes. The repositioned support clamp and rerouted pipe are presented in **Figure 25**.

The number of support rails was reduced from four to two because the pipe was designed shorter than before. The routing of the pipes was simplified and the angles of the bends were changed to even values whenever it was possible. The support rails are shared with the Control Air Pipe. The 3D models of both the old and new pipe designs are presented in **Figure 26**.

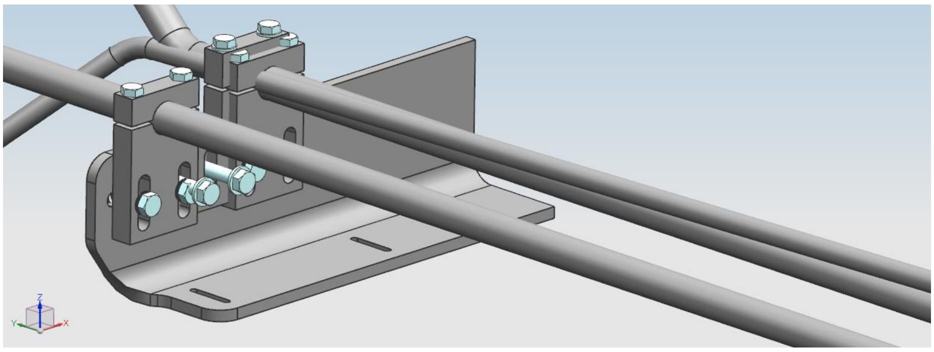

Figure 24. Overlapping of Pilot Fuel Line and Dirty Leak Fuel Pipe.

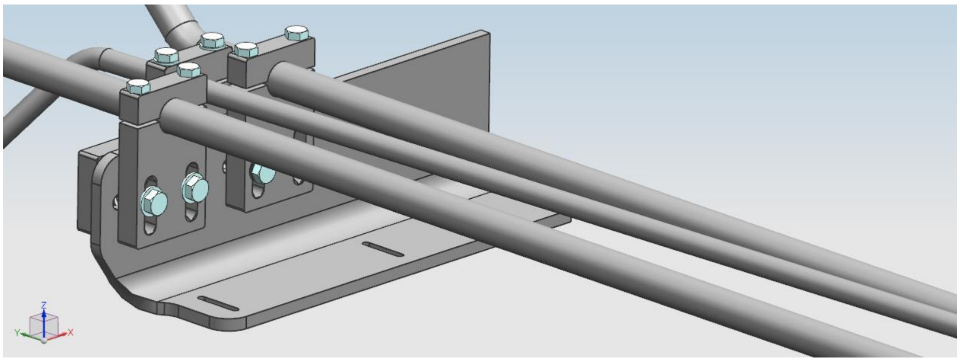

Figure 25. Redesigned Pilot Fuel Line and Dirty Leak Fuel Pipe.

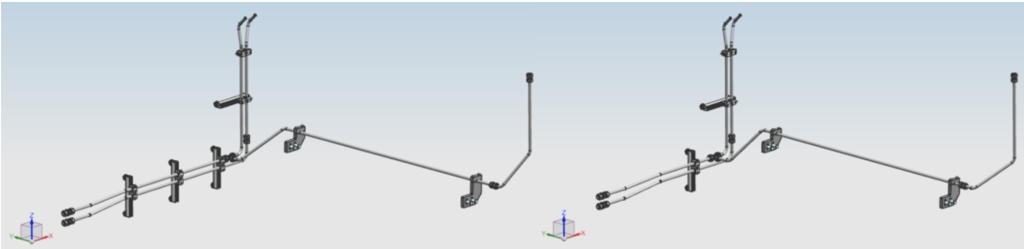

Figure 26. Pilot Fuel Line. (Old & new.)

7.5 Drain Pipe

Reducing the length of the base frame did not affect the condensate water drain pipe. The 3D model of the original design is presented in **Figure 27**.

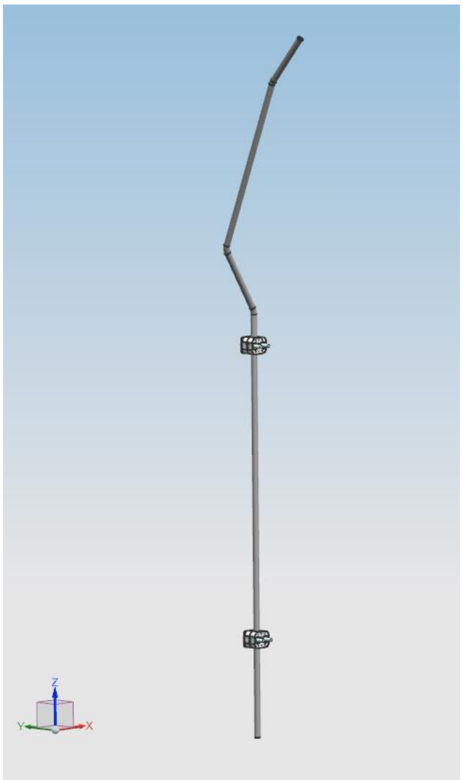

Figure 27. Original Drain Pipe.

7.6 Fuel Pipes and Covers

The length of fuel pipes was reduced by 250mm on the x axis. The length was decided so that the fuel pipe flanges would be as close to the free end water pipe flanges as possible but not so close that the engine tarpaulin would be stretched and torn because of the sharp edged splash guard during transportation. The routing of the fuel oil inlet was simplified and the number of bends was reduced from two to one as can be seen from **Figure 28**. The position of the support clamps was adjusted to be as close to the flanges as possible. The lower cover for the fuel pipes was modified to be simpler in order to make the manufacturing easier and cheaper. The 3D models of both the old and new pipe designs with the covers on are presented in **Figure 29**.

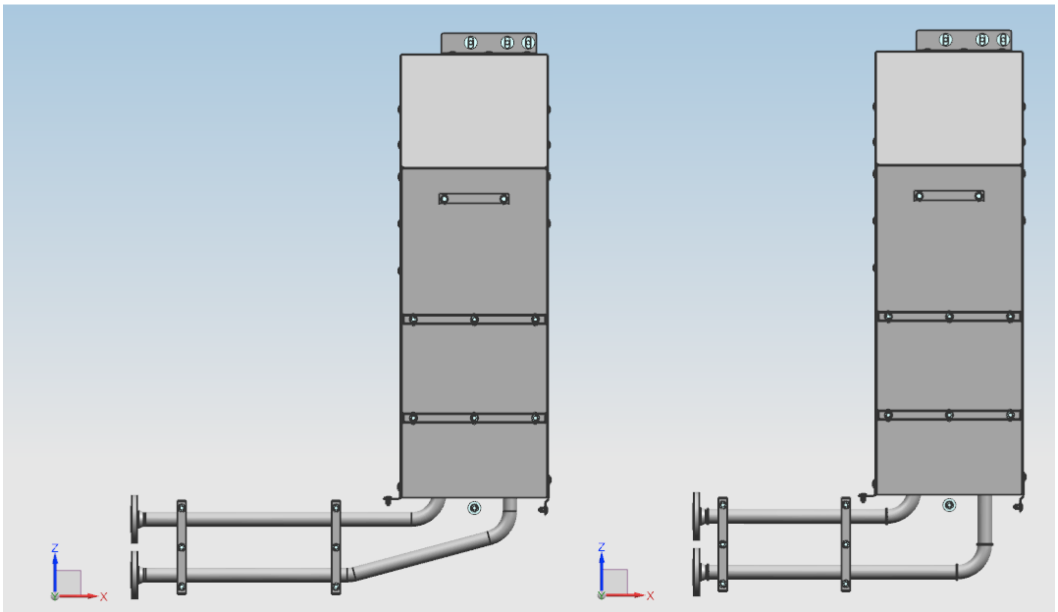

Figure 28. Fuel Pipes without lower covers. (Lower: FO inlet, upper: FO outlet.)

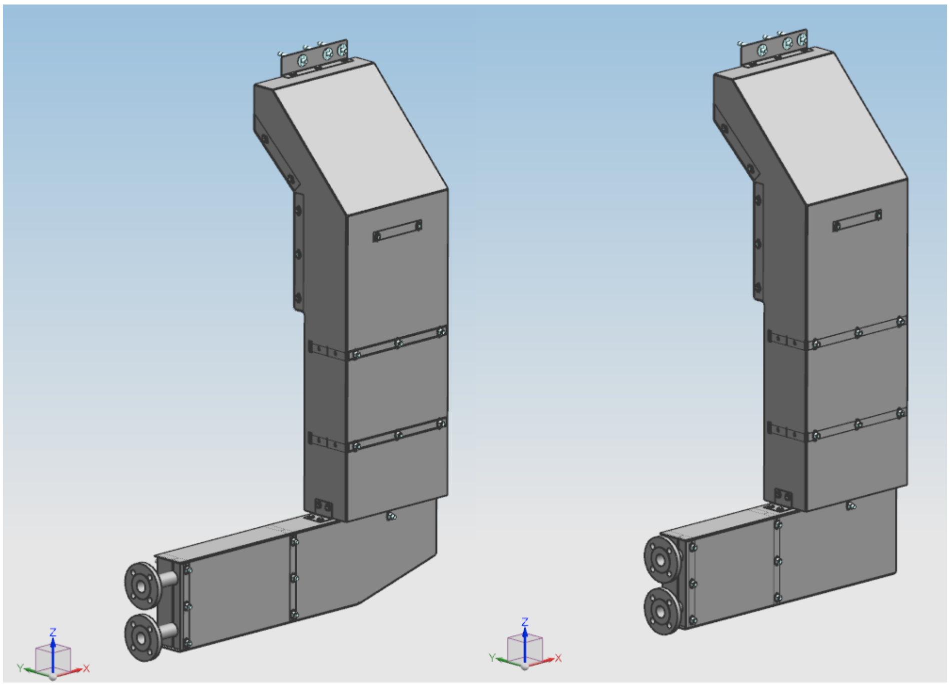

Figure 29. Fuel Pipes with lower covers. (Old & new.)

7.7 Lubricating Oil Pipes

The LO pipes were not in the scope of the thesis work. They are not included in 20V34DFB 1–C but instead used in the heat recovery genset solution. The LO pipes had to be rerouted to fit to the shorter base frame to ensure that the pipes within the scope would not clash with them when used in the same genset.

The LO pipes could not be routed so that only the bent pipes could be used due to a difficult location. The reducer of the LO inlet was changed from 140mm long to 85mm so that the same welding bends, 3D R190, could be used for both pipes to decrease the manufacturing costs /7/. The LO inlet needed two welding bends and the LO outlet needed one while the rest of the pipe could be bent.

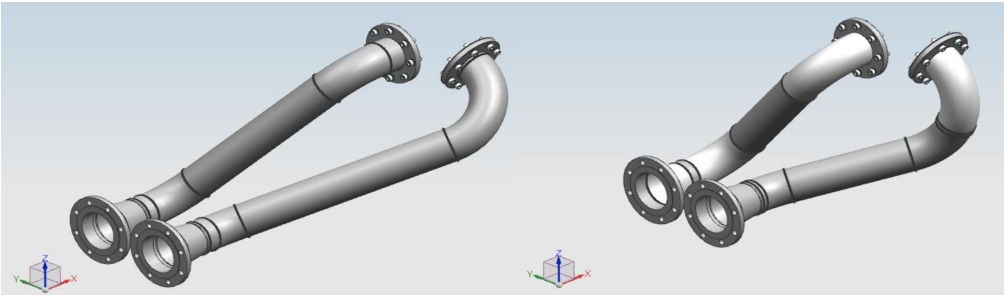

Figure 30. Lubricating Oil Pipes. (LO Inlet & LO Outlet, old & new, welding bends and new reducer highlighted.)

8 CONSTRUCTION OF THE FEM MODEL

The 3D models made in NX were imported into Abaqus as Parasolid models. The imported models were simplified in order to generate a lighter calculation model. The parts were tied together with tie constrains into the subassemblies. The final calculation assembly was connected to the spring elements that are fixed to the ground.

8.1 Simplification

The 3D models were simplified for simulation purposes to present the reality in an optimal way. The number of elements and nodes can be drastically decreased with this effort. The chosen solution was a compromise between accuracy and computing time as is usual in FEM calculations.

The Element Mesh can be distorted by small details as for example holes, chamfers and bends. These were removed in order to make the element mesh and the element size more consistent. The removal of the details does not affect in calculation results as the modelling is made with expertise.

In most components, the model shell was extracted by creating a middle surface to the sheet or pipe structures and assigning correct material properties to it. These properties included thickness, density, Young's modulus and Poisson's ratio. Complicated structures that could not be presented correctly as shell models were left as three dimensional and therefore the thickness was not assigned. The extraction of middle surface is presented in **Figure 31**.

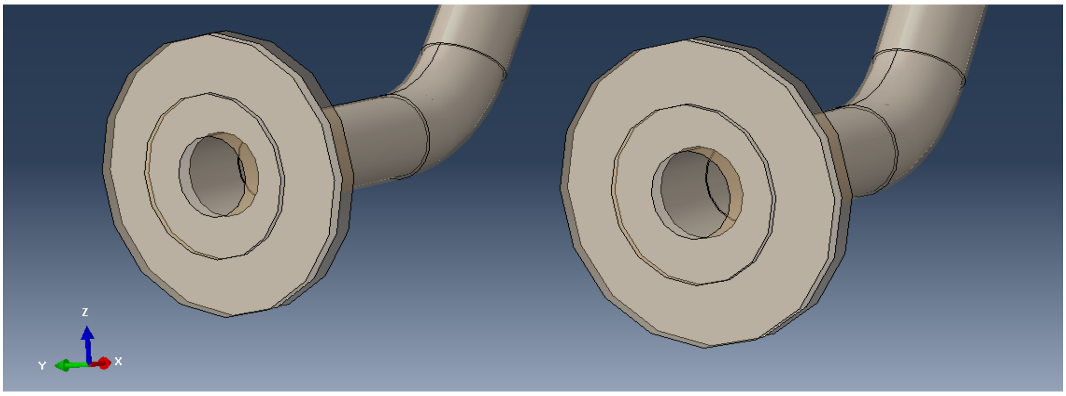

Figure 31. The extraction of middle surface. (LO Pipes, Abaqus.)

8.2 Element Mesh

The shell models were meshed with the Quad–dominated mesh. It had mostly linear quadrilateral elements and some linear triangular elements to complete the shape. The shell mesh was used for 89% of the parts in the free end pipes and the base frame. The shell meshed mounting plate is presented in **Figure 32**.

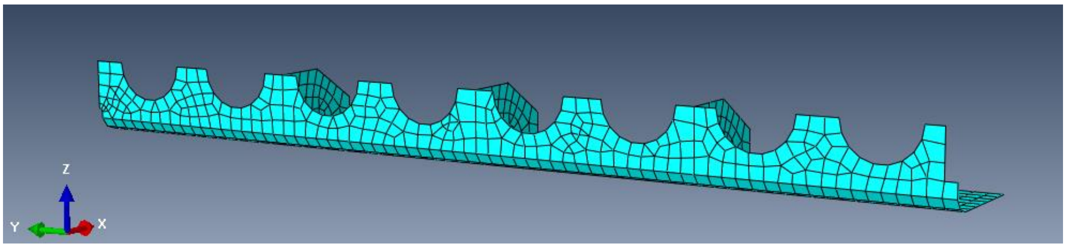

Figure 32. The Mounting Plate meshed with Quad–dominated elements.

Few parts had to be left as three dimensional to present their structure properly. Tetrahedral elements were used for these parts. The problem with solid parts and 3D elements is that the number of elements is much higher than with shell models and 2D elements. This creates very heavy FEM models with a high number of variables that are very demanding to calculate. The solid meshed mounting plate Supports are presented in **Figure 33**.

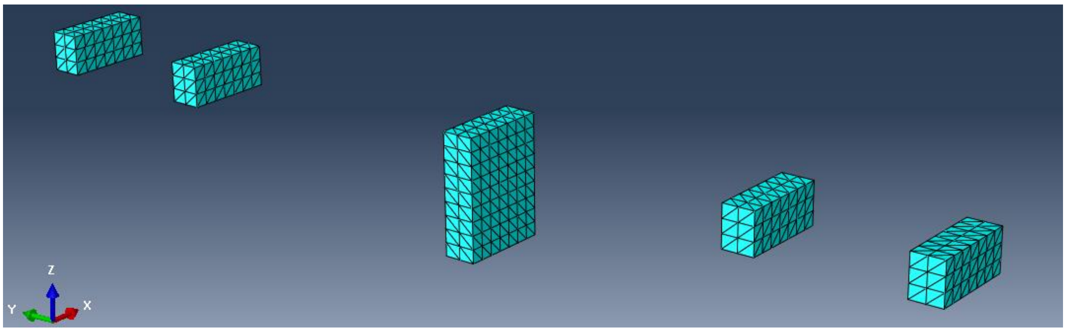

Figure 33. The Mounting Plate Supports Meshed with Solid Tetrahedral elements.

8.3 Mass

Masses are very important material properties in the natural frequency calculations along with the stiffness properties. An unofficial rule in the FEM calculation is that the mass should be within 10% variation of the real mass for complex models. With these margins the results can be considered accurate concerning masses.

Complex and detailed components make the calculation model heavier and it is sensible in some cases to simplify the components. The volume of the component changes during these simplifications and no longer represents the right mass for the component. In these cases, materials with right stiffness properties without mass can be assigned to the components. The lack of mass can be substituted with the right amount of nonstructural mass.

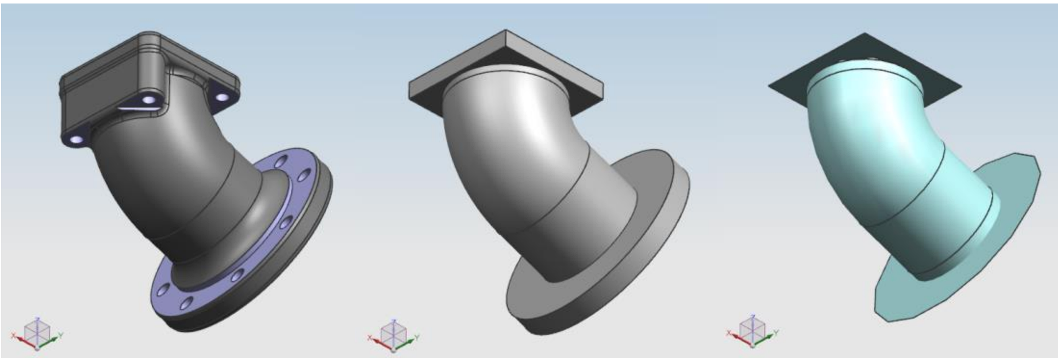

Figure 34. Example of the simplification of a component. (The Water Bend.)

8.4 Constrains

The normal connections between components were made using a tie constrain with two surfaces. The area of constrainable surface was specified according to unofficial FEM rules to achieve a realistic behavior and accuracy.

8.5 Boundary Conditions

The boundary conditions are the representation of the boundary layer connection between the FEM model and the outside world. The boundary condition can constrain a different number of degrees of freedom depending on the situation. In the boundary conditions of the 20V34DF Genset model, the base frame is attached to spring elements which are constrained to the ground by removing all six degrees of freedom. The right stiffness values were defined for the spring elements.

8.6 Substructures

Due to the large sizes of the calculation models, it is not always practical or possible to use normal models as a calculation background. Computing time rises and working with the model becomes slow. Substructures, also known as super elements, are a great option to represent the original model with an adequate accuracy but with a much lighter computing load.

Substructures are especially beneficial in models that are large but not interesting in a detailed level in the analysis. Once eliminated and calculated DOFs are not necessary to calculate again in every analysis and the calculation becomes lighter. In this case background structures are good examples: they are large and heavy, but needed just for generating a realistic model. /12/

8.7 The FEM Models

The final FEM calculation model consists of different subassemblies that are created separately in the Abaqus CAE. All models are brought together in a modified input text file. The input file contains node, element and surface definitions and tie constrains.

When models and input files are made carefully and in compliance with calculation rules and norms, this assembly method has a few advantages. Modifications to the model are easier as they can be directed to smaller subassemblies. The changing of subassemblies in the master assembly model is very easy on the input level. This needs to be done for example if some component of the genset is replaced to different one.

However, when many separate models are included into one model, there can be no overlapping. Usual error messages include more than one nodes or elements that have the same number. Materials and sections cannot have the same names in different models if those models are included in the same file. These problems can be avoided with FEM model construction rules and standards. Scripts have been also made to ease up the work in input files.

8.7.1 Free End Pipes

The free end pipes model was constructed with shell elements. All pipes with diameter under 42 mm were excluded from the model as they are not significant in the analysis and can reduce the accuracy of the analysis results. The mass of the excluded pipes was added as nonstructural mass to the base frame.

The material properties of the cast iron were assigned to the LT water inlet and the water bend. Due to the approximate structure of the water bends, the valves and part of the fuel pipes, their mass was represented by nonstructural mass. The conclusive mass of the FEM model was 733 kg whereas the mass of the more detailed structure model was 675 kg. The final difference was ~8% which sets between the limits of reasonable variation of the mass. The mass of the liquid inside large pipes was added in the model after mass verification as a nonstructural mass.

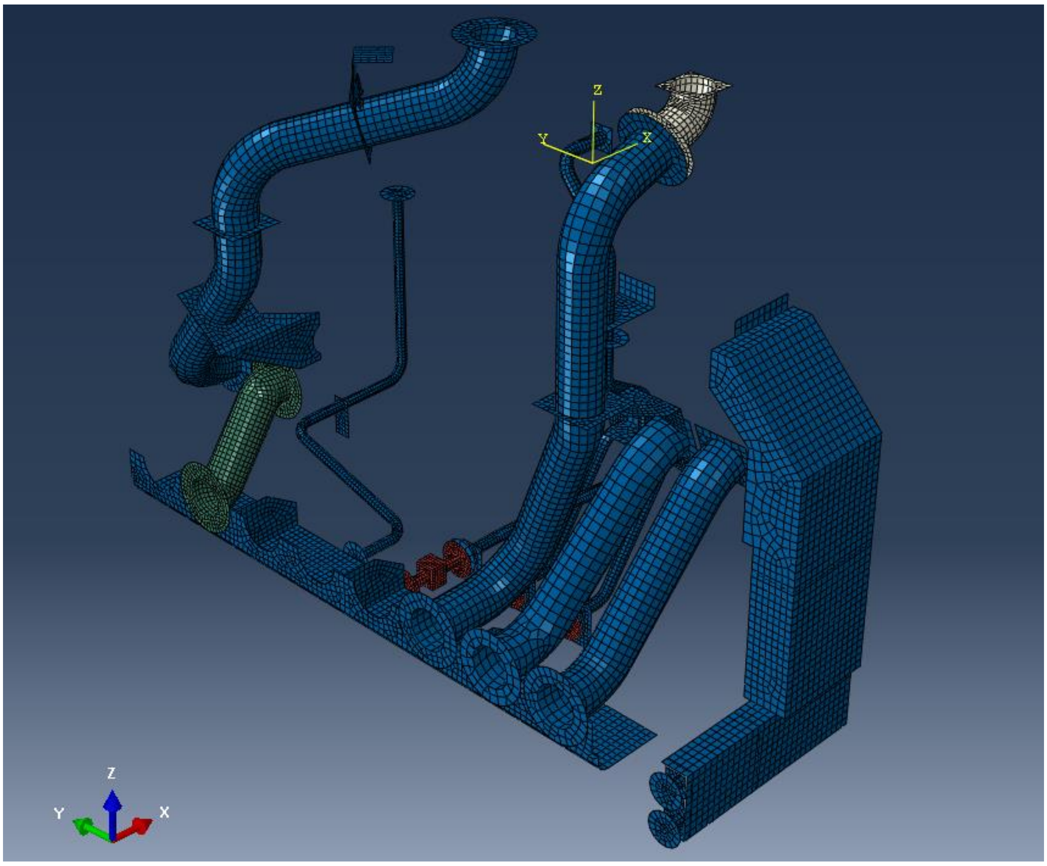

Figure 35. Element mesh of the free end pipes.

8.7.2 Base Frame

The common base frame was constructed mostly with shell elements. Tetrahedral elements were used for the top plate, the mounting plate supports and the lifting pins. The material properties of all parts represented steel.

The conclusive mass of the FEM model was 18623 kg whereas the mass of the more detailed structure model was 18133 kg. The final difference was ~2.6%, which sets between the limits of the reasonable variation of the mass.

8.7.3 The FEM Background

The scope of the background in the FEM model was one issue to consider in the natural frequencies calculation. The background itself did not have any components of interest concerning the natural frequencies. The surrounding background has an effect on the components of interest. Meaning that more complete model, the more accurate the results of the free end pipes and the base frame. It was decided that the complete model will be used. Based on this the 20V34 Genset FEM model was fully constructed

Finally, the background models were made into two substructures, one for the generator and one for engine and its components. This procedure lightened the computing load significantly.

9 CALCULATION AND ANALYSIS OF THE FREE END

9.1 Calculation

The natural frequency calculation for the 20V34 Genset model was done with Abaqus. The frequency scope under examination and eigensolver were chosen to extract natural frequencies from the model.

9.2 Analysis

Analyzing the natural frequencies was done by visually examining the natural modes. The frequencies of the modes were then compared to known critical excitations of the engine in the genset. If the frequencies of the modes were close, approximately 2 Hz, to the critical excitations, it could be considered alarming.

10 RESULTS

The objective was to research local natural modes of each large free end pipe and parts of the base frame. Global modes would also appear on the calculation results but they were more related to the structure of the whole genset than a single instance. After locating the local natural modes, it was investigated if the modes would respond to the excitations by comparing the data.

It was researched that some excitations from the engine were more severe than others. Avoidance of these excitations was the highest priority. The second priority was to shift natural modes to higher frequency areas because as the frequency rises, the amplitude of the vibrations gets smaller and vibrations are not as critical.

10.1 Local Natural Modes

The shortening of the base frame made the free end of the genset very stiff. Local natural modes within the area of frequencies in examination could not be found for all pipes in the free end. The pipes that had natural local modes were Low Temperature Water Pipe and High Temperature Water Outlet from Air Cooler. In the common base frame, side plate B had multiple local modes. The components are identified in **Figure 36**.

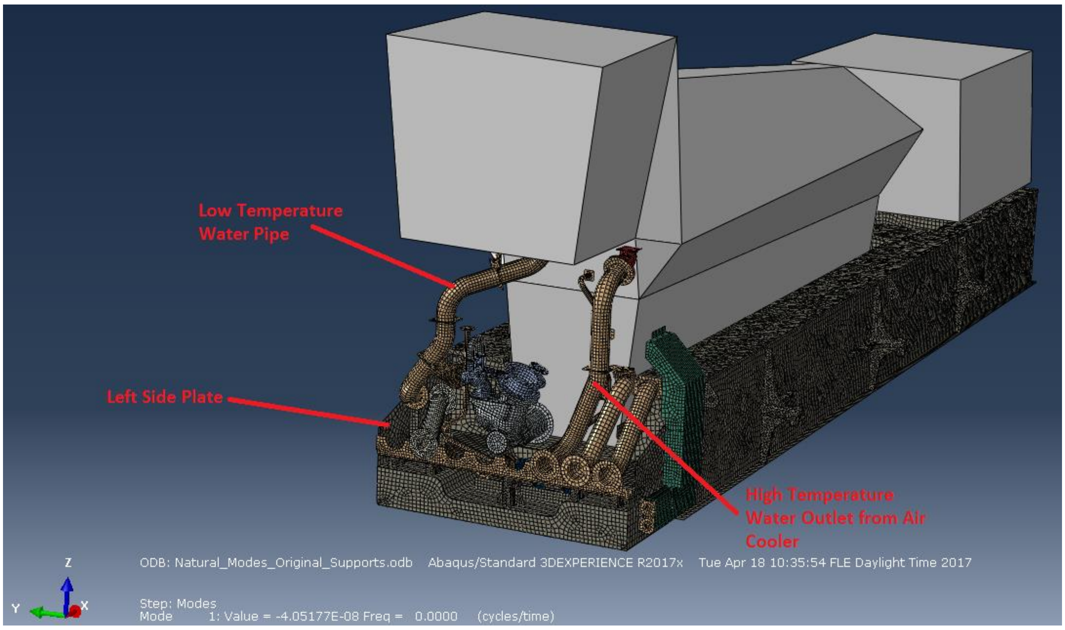

Figure 36. Components with local natural modes.

10.2 Low Temperature Water Pipe

The Low Temperature Water Pipe seemed to be the most difficult pipe concerning natural modes. The reason for that was supposedly the high mass and long length of the pipe.

10.2.1 Original Supports

The low temperature water pipe with the original supports had local transversal modes in frequency range of 72,9Hz to 81,5Hz. Some of these natural modes were in low critical areas of excitations.

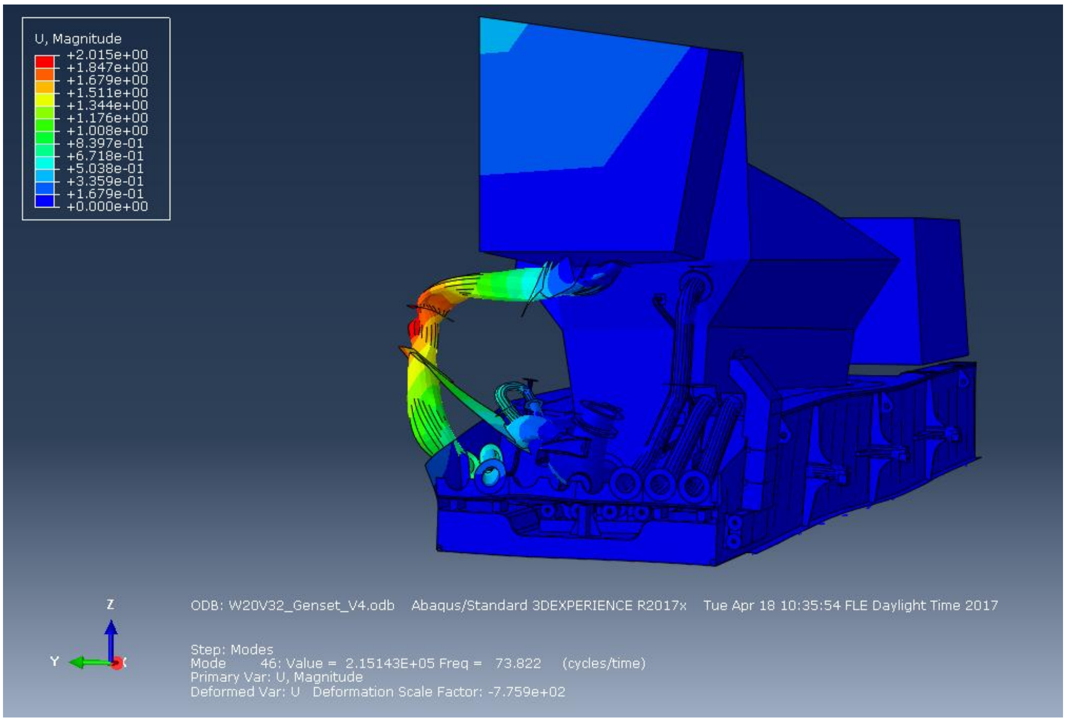

Figure 37. Local transversal natural mode of LTWP at 73.8 Hz.

Table 1. LTWP local natural modes with original support

Frequencies of local transversal natural modes of Low Temperature Water Pipe				
72.9 Hz	73.8 Hz	78.8 Hz	80.7 Hz	81.5 Hz

10.2.2 Optimized Support

The support of the LTWP was changed to be stiffer in lateral direction. The new support was connected to the oil suction pipe and closer to the middle point of LTWP. The changes made the natural modes of the pipe shift to higher frequency area than was intended. The first fully local natural mode of the LTWP is at 85.7 Hz. The pipe participates in the natural mode with lubricating oil pump (represented as point mass in FEM model) at 79.5 Hz in the low–critical frequency range.

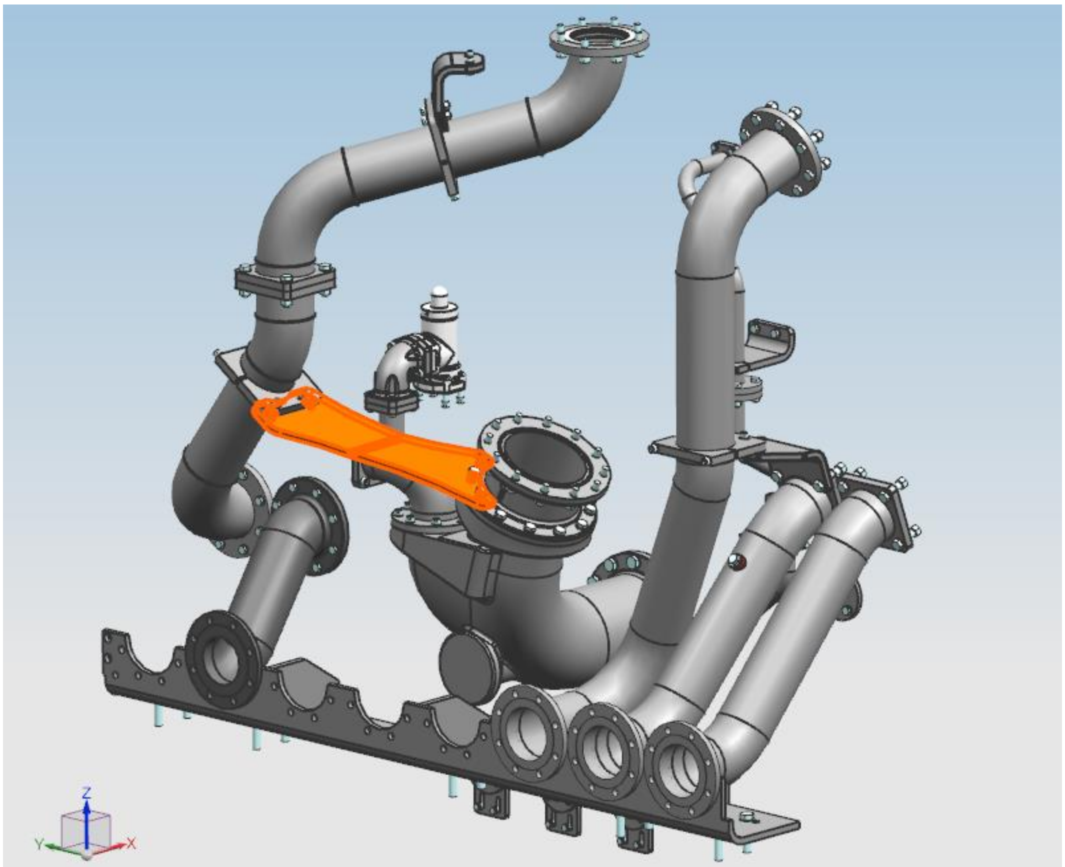

Figure 38. New support for LTWP highlighted.

Table 2. LTWP local natural modes with optimized support

Frequencies of local natural modes of LTWP with optimized supporting						
79.5 Hz	80.7 Hz	83.7 Hz	84.7 Hz	89.0 Hz	96.0 Hz	99.0 Hz

10.3 High Temperature Water Outlet from Air Cooler

Without any supports, the High Temperature Water Outlet from Air Cooler had four different natural modes between 66.9 Hz and 79.2 Hz. After the pipe was supported to the High Temperature Water Inlet, all local modes disappeared from the frequency range in examination.

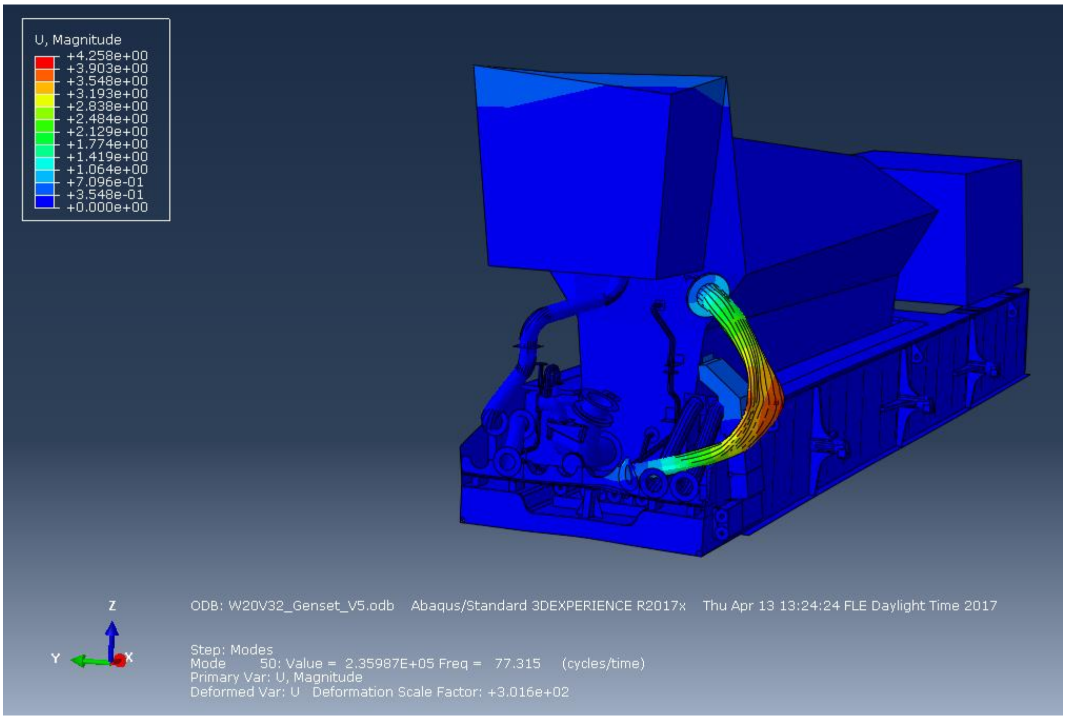

Figure 39. Local transversal natural mode of HTWOfAC at 73.8 Hz.

Table 3. HTWOfAC local natural modes

Frequencies of local natural modes of the HTWOfAC without support			
66.9 Hz	69.6 Hz	77.3 Hz	79.2 Hz

10.4 Side Plate B

10.4.1 Original Supports

Side Plate B turned out to be very prone to transversal natural modes. Side Plate A was supported well by fuel pipes. In the SG version of the engine, fuel pipes are not present and natural modes should be studied or measured because the results of this calculation are not valid.

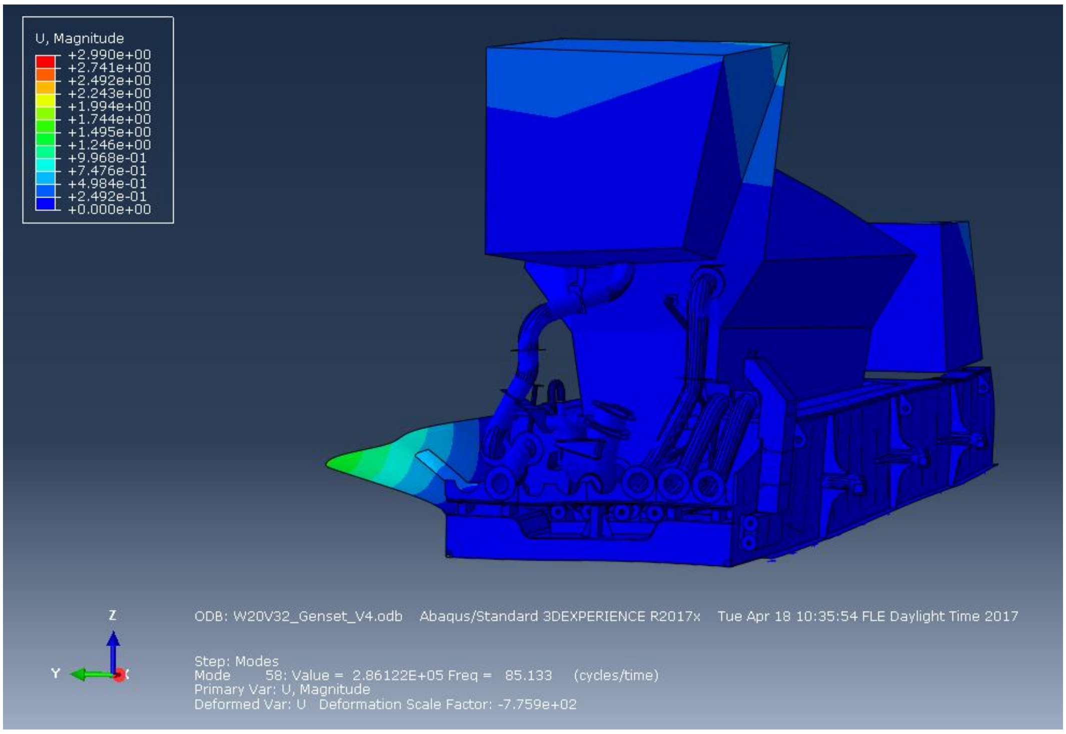

Figure 40. Local transversal natural mode of Side Plate B at 85,1 Hz.

Table 4. Side Plate B transversal natural modes.

Frequencies of local transversal natural modes of Side Plate B				
51.9 Hz	57.8 Hz	60.0 Hz	70.8 Hz	84.3 Hz
85.1 Hz	87.9 Hz	88.6 Hz	89.1 Hz	91.1 Hz

10.4.2 Optimized Structure and Supports

The number of supports was increased to two and the supports were modified to be sturdier. The bend radiuses of side plates were made bigger from 30mm to 300mm. These modifications made the natural modes of Side Plate B shift to a higher frequency range or disappear altogether. Side Plate B is still involved in some global natural modes.

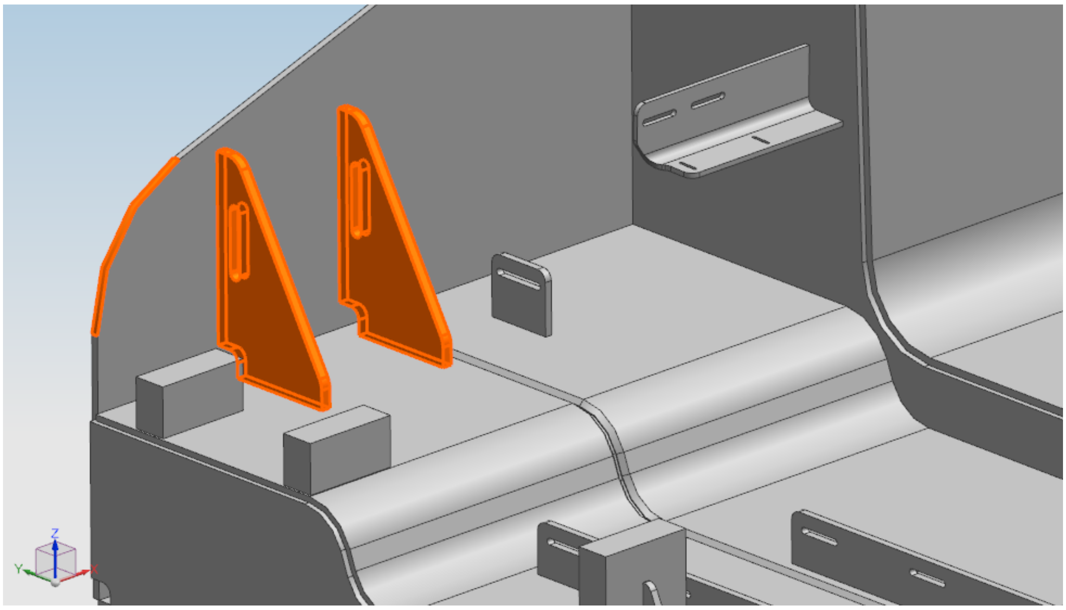

Figure 41. Optimization modifications highlighted.

11 CONCLUSIONS

11.1 Structural Design

The structural design work went according to plan. Even some details could be considered during the design and overall there were many possible improvements to the earlier design. The improvements could decrease the cost, wasted material and manufacturing difficulty. A few challenges came up with the pipe designing due to pipe lengths, bend radiuses and supporting points. All the problems could be solved.

11.2 Construction of the FEM model

The construction of the original FEM model went well and was ready early. However, the model appeared to be too heavy to deal with and the calculation time was not reasonable. The answer to this challenge was to create substructures for the heavy background models. This was something new to me and at times, working with the substructure was frustrating and there seemed to be no progress. This delay was the only occurrence of doubt about the schedule and deadline in this project. All of a sudden the work started to go forward and soon the FEM model was ready.

The FEM model was done carefully and it should be a good representation of the natural frequencies of the real genset. The sub-models were made to be easily altered and replaced if there ever was need for it. Even though the second stage was challenging and the progress slow at times, the outcome can be considered good. The final calculation model was well made with light computing load. Learning of the substructure creation was also valuable thing.

11.3 Calculation, Analysis and Optimization

The challenging components of the free end were found out after the first few calculations. The results were surprisingly good as there was only three locations with local natural modes in the examination range of frequencies. The natural modes were easily shifted for the two of the three locations with problems. Last remaining challenging component, low temperature water pipe, had only a few supporting locations in the reasonable range. Each one of the different options seemed not to stiffen the pipe enough to shift the natural modes to the safe area of frequencies. The final possible support with connection to the oil suction pipe was sturdy enough to shift the natural frequencies of the LTWP to over 79,5 Hz.

11.4 Evaluation of the Results

The shortening of the free end of the generating set turned out to be possible as all the pipes could be fitted to new connection points. The aim length of the shortening, 432mm, was accomplished. The shortening of the base frame made it stiffer which was the main reason for this project.

The redesign of the free end pipes can be considered a success as in addition to fitting the pipes to shorter base frame, the manufacturing cost could be decreased for some of the pipes. Decreasing the costs was achieved by designing the pipes in a way that they could be made with cheaper manufacturing methods. In a few cases, the premanufactured bends could be bended as a part of a pipe which removes the cost of the part and the cost of the welding the parts together.

After calculating the natural frequencies of the generating set for the first time it was clear that the whole free end was quite stiff as hoped. The shorter pipe design and a few added supports for large pipes, such as the Low Temperature Water Pipe and the High Temperature Water Outlet from Air Cooler, had stiffened the structure of the pipes considerably. There were only two locations left to optimize by modifying the supporting and structure.

The local natural modes of Side Plate B were shifted to higher frequencies away from the critical excitations very easily by modifying and adding supporting. The Low Temperature Water Pipe proved to be more challenging to support stiffly. A suitable supporting location was found on the oil suction pipe after some experimenting. With the new support, only one natural mode in participation with the lubricating oil pump was remaining in the low–critical frequency range.

The results were discussed with colleagues. As the frequency of remaining natural mode is high (79.5 Hz), the vibrations have a small amplitude and therefore are not as critical as lower frequency vibrations. The knowledge and experience in field work has shown that critical vibrations normally take place under 70 Hz. Considering these and the facts that the excitation in the frequency area is low–critical and that the natural mode is not fully local, the support of the pipe can be considered well adequate for its purpose.

All objectives of the thesis were completed. The design of the free end of the generating set is now in a good state for further development. According to the calculations, there should not be problems in the free end with vibrations. Measurements will be carried out to confirm the result of the calculation once the product is ready.

11.5 Utilization of the Thesis Work

The new design for the free end will be most likely put to use. For pipes and supports, there is no additional calculations to conduct. If there are no obstacles and they are approved, they will be used as designed. The entire common base frame is being calculated and redesigned at the moment. The updated new free end design is implemented into the redesign work and later taken in use in real projects.

The next step will be a creation of new manufacturing drawings for all the modified parts, components, subassemblies and assemblies. After manufacturing drawings are checked and approved, the project will be ready and can be utilized in real life projects.

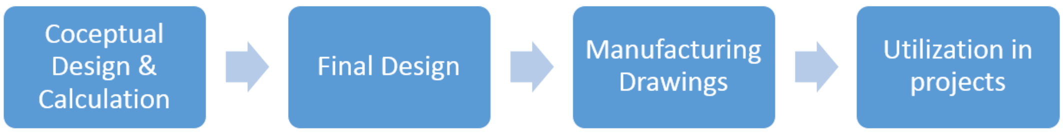

Figure 42. Process to utilize thesis work in real world projects.

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